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GRANULAR CARBON TREATMENT OF RAW SEWAGE

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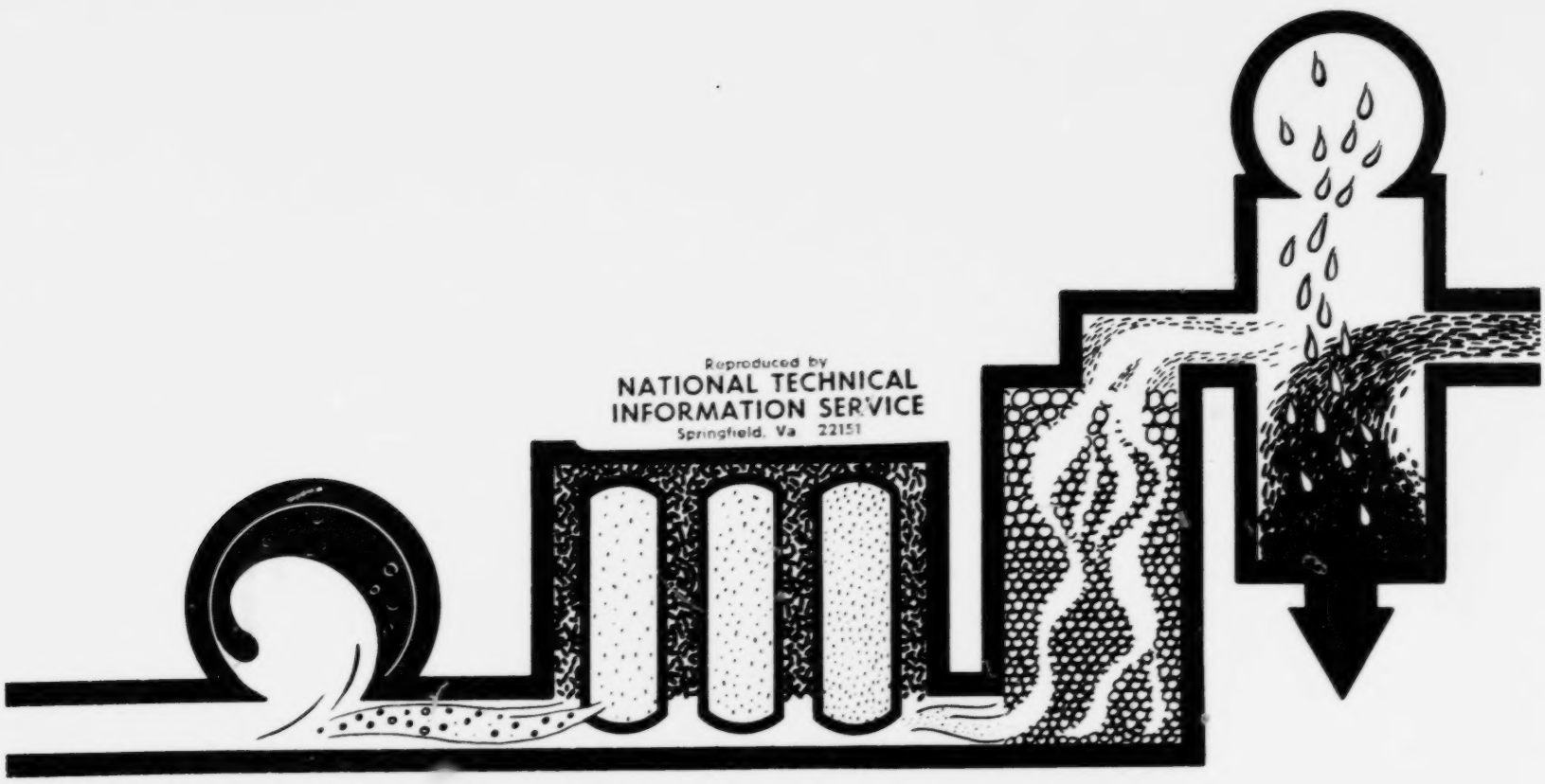

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27 Abstract: A comparison was made of expanded-bed and packed-bed modes of operation of activated carbon adsorption systems in the direct physico-chemical treatment of raw sewage and primary effluent. This project involved extended field testing of a pilot scale treatment system of chemical clarification followed by adsorption. The expanded-bed and packed-bed modes of operation demonstrated essentially equivalent removal of organic matter from the chemically clarified effluent. When a 24 ft. settled depth of activated carbon was used, both systems consistently produced a clear, treated water with an average organic content of only 3-5 mg/l, measured either as TOC or BOD. The expanded bed mode offered several advantages: (1) it eliminates plugging or fouling with particulate matter and air binding; (2) feed pressure remains constant and maintenance requirements are minimal; and (3) it provides an opportunity for a degree of natural aeration. Estimated cost for treating raw waste water in a 10 MGD plant by this process is about 20 cents per 1000 gal. with a total estimated investment of $4,000,000. (Ellis-Texas)

(revise abstract)

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GRANULAR CARBON TREATMENT OF RAW SEWAGE

by

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for the

FEDERAL WATER QUALITY ADMINISTRATION

DEPARTMENT OF THE INTERIOR

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ABSTRACT

The primary purpose of this study has been the detailed comparison of expanded-bed and packed-bed modes of operation of activated carbon adsorption systems in the direct physico-chemical treatment of raw sewage and/or primary effluent. A major part of the project involved extended field testing of a pilot scale treatment system of chemical clarification followed by adsorption.

Pilot scale operations were carried out at the sewage treatment plant of the Ewing-Lawrence Sewerage Authority (ELSA) near Trenton, New Jersey. Selection of the coagulant and determination of design parameters for the pilot plant coagulation-clarification system were based on extensive laboratory investigations of the coagulation of the Ewing-Lawrence raw sewage and primary effluent. Ferric chloride was chosen for use as the coagulant in the pilot operations. Equivalent clarified feeds for the adsorbers were produced from raw sewage and primary effluent with the same coagulant dosage. The pilot study was carried out with primary effluent as feed to the system.

The expanded-bed and packed-bed adsorbers were constructed of plastic-coated 10-in. diameter steel pipe. These adsorbers, each containing a 6-ft settled depth of activated carbon, were arranged so that expanded-bed and packed-bed units of up to 24-ft carbon depth could be operated in parallel at specific feed rates of 5-7 gpm/ft^2. These studies extended over a period of one year with the longest single run of the pilot system being 125 days.

The expanded-bed and packed-bed modes of operation demonstrated essentially equivalent removal of organic matter from chemically clarified primary effluent. When a 24-ft settled depth of activated carbon was used, both systems consistently produced a clear, treated water with an average organic content of only 3-5 mg/l, measured either as total organic carbon (TOC) or biochemical oxygen demand (BOD).

The expanded-bed mode of operation offers several distinct advantages. First, expanded-bed operation essentially eliminates plugging or fouling with particulate matter and air binding, both of which cause high pressure losses and frequent back-washing requirements for packed-bed operation. In the expanded-bed system, feed pressure remains constant and maintenance requirements are minimal. Further, expanded-bed operation provides the opportunity for a degree of natural aeration between contacting stages which may be important to the production of a stable, treated water.

Clarification with ferric chloride was found to remove over 90% of the solids and at least 60% of the TOC from the wastewater, including about 30% of the organic matter classified by membrane filtration as soluble (SOC). In addition, phosphate,

which is not normally removed to any appreciable extent in conventional biological treatment of wastewater, was reduced by over 90% during chemical clarification with the ferric chloride.

The combined direct treatment system of chemical clarification followed by adsorption in expanded beds of activated carbon maintained, over a period of 125 days, an average of 93% removal of organic matter from the primary effluent (equivalent to greater than 95% removal from the raw sewage), measured as either TOC or BOD. This performance was maintained in spite of variations in waste composition which would adversely affect conventional biological processes. Even under the best of operating conditions, conventional biological treatment cannot produce nearly as high a quality effluent as was obtained by this direct clarification-adsorption treatment. In addition, it was demonstrated that further treatment of the effluent with a small bed of fresh carbon could reduce the organic content to 1-2 mg/l TOC.

Estimated cost, on a realistic 1969 economic basis, for treating raw waste water in a 10 mgd plant by this process to produce a high quality water is 20 cents per 1000 gal. with a total estimated investment of $4,000,000. Expanded-bed operation is slightly less costly than packed-bed operation. If tertiary facilities were added to a conventional treatment plant to provide an effluent of the same high quality, most of the foregoing costs would be incurred in addition to the costs for the conventional primary-secondary treatment.

This report was submitted in fulfillment of Program No. 17050 DAL, Contract No. 14-12-459, between the Federal Water Quality Administration and FMC Corporation.

INTRODUCTION

A previous investigation[1] conducted by the FMC Corporation for the Federal Water Pollution Control Administration demonstrated that expanded-bed operation of granular activated carbon contacting systems offers certain advantages over fixed or packed-bed operation for the advanced treatment of secondary effluents. Upon examining the results of other preliminary studies on the direct physicochemical treatment of raw sewage[2], and on consideration of the nature of the organic matter present in raw sewage relative to that in secondary effluent, the conclusion was drawn that activated carbon treatment of sewage without prior subjection to biological treatment could be highly effective and that the expanded-bed mode of contacting might have considerable advantage for such treatment. As a result, the treatment of settled sewage or primary effluent by carbon adsorption was investigated on a pilot scale and, as in the earlier investigations with secondary effluent, expanded-bed adsorption systems were compared with fixed-bed systems, for which some other experience had been reported in the literature.[3]

Research on an essentially physicochemical method of treatment of sewage is highly desirable because it has become increasingly apparent over the past several years that achievement of high levels of water quality demanded by progressive water use and reuse requirements, and by requirements for more effective water pollution control, necessitates the application of improved techniques for waste water treatment. Conventional secondary biological treatment processes do not provide the degree nor the consistency of treatment requried for most water reuse applications, nor do they provide a completely satisfactory means for protecting natural waters from pollution by waste discharges.

Well operated, modern biological sewage treatment plants can provide approximately 95% removal of suspended solids (SS) and reduction of BOD to 20 mg/l BOD but have difficulty maintaining this level of treatment on a continuous basis. Although the quality of the effluents from such plants has been considered adequate to meet most discharge regulations and effluent standards in the past, increased concern over the quality of surface waters, and the problems of meeting increasing water demands from a relatively fixed total water resource, have resulted in more stringent demands for better water quality and more effective pollution control. As a result, significant interest has focused over the past decade on development of physicochemical processes capable of consistently accomplishing the degree of treatment required by more stringent effluent standards.[4,5]

Research and development on advanced physicochemical processes for wastewater treatment has primarily been centered on providing tertiary treatment for wastes which have already undergone conventional secondary biological treatment. The addition of tertiary-level physicochemical processes to

conventional secondary-level biological processes incurs significant additional treatment expenses. Further, the effective operation of a tertiary treatment system is dependent on the consistent and efficient operation of the biological secondary process, which remains subject to problems arising from changes in waste composition, from large variations in flow which have often had to be diverted, and from the presence of toxic materials which disrupt biological oxidation processes.

The present work represents a major diversion from the traditional concept of tertiary treatment and examines the use of expanded-bed adsorption as a direct application of the physico-chemical process for treatment of primary waste.

The concept of applying such a treatment directly to a primary waste, rather than to a secondary effluent, derives partially from observations regarding the apparent difficulty of removing final traces of organic matter from secondary effluents by treatment with activated carbon, as well as from the relative economics of two-stage vs. three-stage treatment systems. Several investigators have reported leakage of certain organic fractions through activated carbon columns when the latter were used to treat secondary effluent.[6,7] The nature of this leakage is not exactly known, but, there is strong indication that it is comprised partially of nonadsorbable bacterial cell fragments and partially of small organic molecules which have been extensively hydrolyzed in the biological treatment stage and thus rendered more soluble and less subject to adsorption. These observations suggest that a primary wastewater might therefore be more suitable for direct treatment with activated carbon than it would be after having undergone biological treatment. Laboratory studies were performed several years ago to test this hypothesis and the results indicated that high levels of removal of organic material could be obtained.[2]

OBJECTIVES

The objectives of this project were to determine, on a pilot scale, the feasibility of removing organic materials from primary effluent or raw sewage using granular activated carbon in expanded-bed adsorbers. Within this overall project objective, specific experimental objectives were:

- To obtain sufficient data on a pilot scale for the expanded-bed contacting system to demonstrate effective performance, to prepare a preliminary design of a treatment process, and to estimate the cost of the process.
- To compare the performance of expanded-bed and fixed-bed adsorption systems.
- To obtain data on the effects of pretreatments and post-treatments for removal of suspended solids.
- To determine the need for aeration in the carbon-bed systems to prevent septicity and to remove biological materials from the carbon particles.

SUMMARY AND RECOMMENDATIONS

The results of the experimental pilot-scale studies presented in this report indicate that expanded-bed activated-carbon adsorption can consistently, effectively, and relatively economically treat a chemically coagulated and clarified raw sewage or primary effluent to produce a clear high quality effluent. This mode of adsorption demonstrated a high degree of utilization of the capacity of the activated carbon, and a potential for using biological activity in the adsorbers to add to the organic removal capacity of the carbon bed, thus reducing carbon dosage and frequency of regeneration.

Pretreatment by chemical clarification, prior to adsorption, demonstrated excellent capacity for solids removal, for removal of a significant fraction of organic matter classified by membrane filtration as soluble, and for effective removal of phosphates.

Combining the two physicochemical processes of chemical clarification and adsorption offers the potential for achieving economical conversion of sewage to a reusable, non-polluting water by removal of 95-97% of its organic matter, essentially all of its suspended solids and turbidity, and in excess of 90% of its phosphate content. Cost estimates based on current (1969) values indicate that this process can be applied in a 10-mgd plant for a total cost of 20 cents per 1000 gal. of product water, using a two-stage expanded-bed carbon contacting system. A less detailed cost estimate presented in October 1967 for a primary-secondary-tertiary treatment system which would produce an equivalent effluent, indicated 23 cents/1000 gal. for a 15-mgd plant.

The expanded-bed activated-carbon adsorber offers several advantages, including:

- little or no cleaning or backwashing required;
- low, and constant feed pressure requirements;
- the potential for simple aeration between stages, if required; and,
- the potential for promotion of biological growth on the carbon without rapid plugging of the bed.

On the basis of these encouraging results, it is recommended that:

- The expanded-bed activated-carbon adsorption treatment be demonstrated on a variety of clarified sewage and waste streams.
- The preliminary treatment plant design and cost estimate presented here be subjected to more rigorous

design and analysis and be compared with other potential processes for achieving an equivalent high degree of organic, solids, and nutrient removal.

- Process improvements be investigated to further increase the benefit-cost ratio of such sewage treatment.

- Means of capitalizing on the beneficial effects of biological growths in expanded carbon beds be thoroughly investigated.

- Further studies be carried out on the use of a rapidly regenerated, fresh carbon polishing filter to reduce the organic content of the effluent from a carbon adsorption treatment to the ultimate low level on a consistent and long-term basis.

EXPERIMENTAL

TEST PROGRAM

The pilot plant test program for comparing the expanded and packed-bed carbon contacting systems was carried out in several phases as shown in Figure 1.

In the first phase, the effect of primary effluent pre-treatment on the performance of expanded and packed beds of activated carbon for removal of organics was evaluated by using untreated and chemically clarified primary effluent feeds.

In the second phase, the expanded and packed beds were compared in an extended operation with chemically clarified primary effluent as feed.

In the third phase, post-clarification of the effluent from expanded-bed and packed-bed contacting of primary effluent was studied for comparison with results obtained in the second phase.

Supporting laboratory experiments were conducted to select coagulants, develop parameters for the design of the clarification system, and compare clarification prior to and following carbon treatment.

Two special small-scale experiments were conducted: 1) to study the effect of particle size on adsorption rate; and, 2) to evaluate the use of a small bed of fresh activated carbon as a final polishing treatment to produce a water with a minimum organic content.

APPARATUS AND PROCEDURE

Preliminary Studies of Coagulation and Clarification

Standard laboratory jar tests were conducted on a Phipps-Bird gang stirrer with six metal blade stirrers, 1 x 3 in. All tests were run in 1-liter beakers using 1-liter samples of primary effluent. Visual observations of the process at specific time intervals were used to check the various steps. Turbidity, pH and other required analyses were run by procedures described later in this report.

A variety of inorganic coagulants and organic polyelectrolyte coagulants were evaluated over a range of dosages, alone and in various combinations for effectiveness on ELSA primary effluent. Test conditions involved rapid mixing at 180 rpm for 15 minutes followed by slow mixing at 20 rpm for 15 minutes. The samples were then allowed to settle for 30 minutes before measurement of turbidity for evaluation of the degree of clarification.

To develop parameters for designing the pilot scale clarification system, the effects of mixing and flocculation were examined at constant dosage of the selected coagulant. A

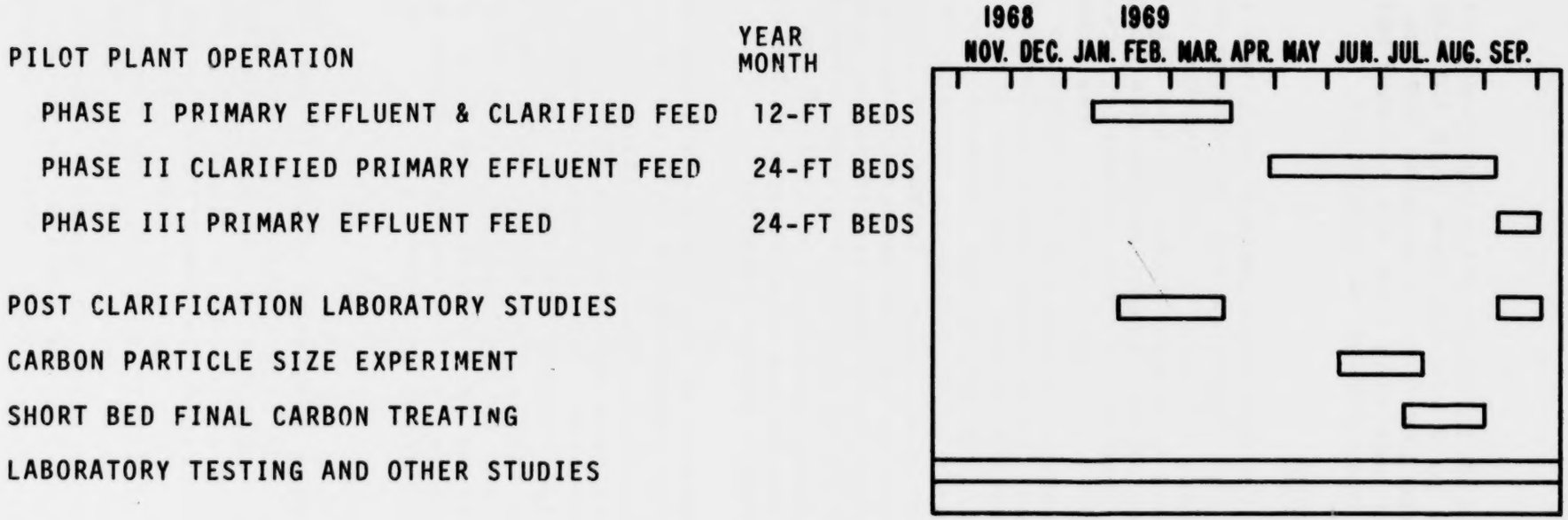

FIGURE 1 TEST PROGRAM FOR STUDY OF TREATING PRIMARY EFFLUENT AND CLARIFIED PRIMARY EFFLUENT IN EXPANDED AND PACKED BEDS OF ACTIVATED CARBON

series of tests was conducted in which stirring speeds of 80 and 160 rpm and times of 0 to 8 minutes were used for the rapid mix period, and 20 to 80 rpm and 5 to 15 minutes for the slow mix period. Thirty minutes settling time was allowed before decanting supernatant for measurement of turbidity.

Pilot Plant Installation

The pilot plant used for the experimental work was the same as that described in the report of the preceeding study on the treatment of secondary effluent in expanded-bed adsorbers.[1] It was located at the sewage treatment plant of the Ewing-Lawrence Sewerage Authority (ELSA) near Trenton, New Jersey which serves residential, commercial, and industrial areas within the two townships of Ewing and Lawrence. The sewage consists of about 25% industrial waste and 75% domestic waste. This is a trickling filter plant which includes four circular, primary sedimentation basins. For this study, primary effluent was taken from one of the sedimentation basins and siphoned through a 300-ft long, 1-1/2 in. polyethylene pipe to a pump at the pilot plant site. Primary effluent was used because of the presence in the raw sewage of varying amounts of solids which would have been difficult to handle in the small lines and valves of the pilot system. The feed to the pilot plant, therefore, consisted of settled raw sewage and, in addition, the liquid from return sludge and supernatant from the anaerobic sludge digestor.

The experimental apparatus at the pilot plant was set up on a poured concrete slab installed for this purpose next to the ELSA return pump building. The coagulation-clarification system, pumps, and controls were located in a 10-ft x 16-ft building constructed on the slab. The carbon adsorbers were internally coated steel-pipe columns resting on the slab and supported by an angle iron frame. The filter and other tanks were located on the slab next to the building. Connections between the columns and valves were rubber hoses which were passed through the building walls. Photographs of the apparatus at the pilot plant site are shown in Figure 2.

Clarification System

The clarification system consisted of two 55-gal. drums for rapid mix, coagulation and flocculation followed by an up-flow clarifier and dual media filter, as shown in Figure 3. The primary effluent was pumped through a float valve which controlled the level in the rapid mix compartment in the upper part of the first 55-gal. drum. The coagulant, a 30-weight percent aqueous solution of ferric chloride, was fed by a metering pump into the stream of primary effluent, discharging from a 5/8-in. nozzle into an elbow to impart a circular motion in the rapid-mix compartment. A motor-driven propeller was used to provide additional rapid mixing. After an average

FIGURE 2a PACKED-BED AND EXPANDED-BED ADSORPTION COLUMNS AND APPURTENANCE. BUILDING IN BACKGROUND HOUSES CLARIFICATION UNITS, PUMPS, CONTROLS, AND AUTOMATIC SAMPLING EQUIPMENT

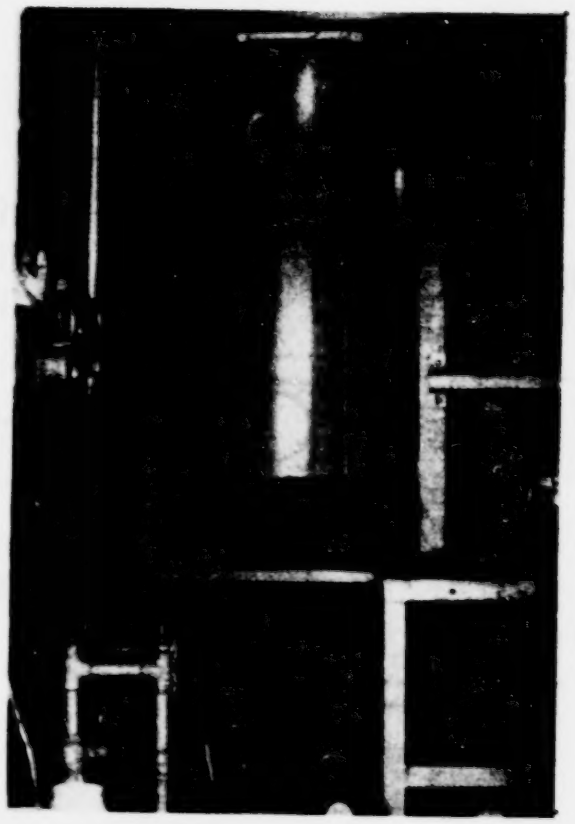

FIGURE 2b UPFLOW CLARIFIER AND PUMPS

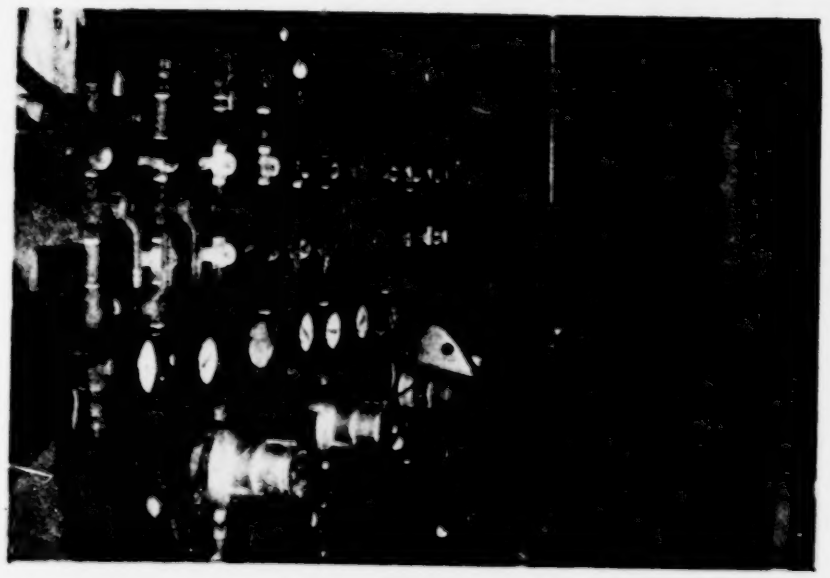

FIGURE 2c FLOW METERING AND CONTROL PANEL

FIGURE 2 PHOTOGRAPHS OF PILOT PLANT INSTALLATION

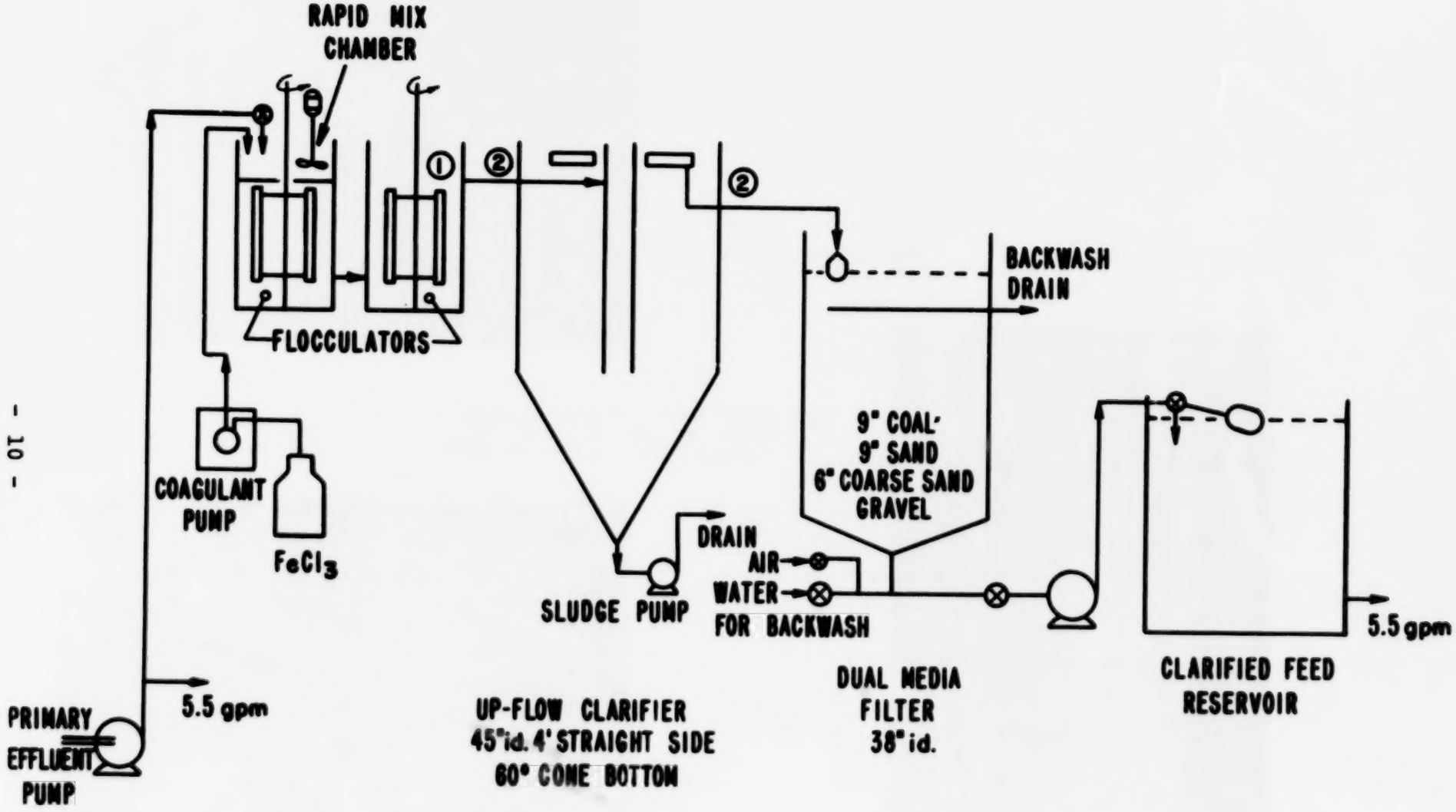

FIGURE 3 FLOW DIAGRAM OF CLARIFICATION SYSTEM

detention time of two minutes at the design flow of 5.5 gpm, the mixture flowed down into the lower part of the first drum for flocculation with slow mixing, into the bottom of the second drum for further flocculation with slow mixing, then out at the top and into the clarifier. The slow stirring in both tanks was provided by 24-in. x 2-in. x 1/2-in. redwood paddles mounted, with the 24-in. dimension in the vertical position, at a 7-in. radius to a vertical shaft driven by a constant speed motor. The first flocculation tank was also fit with three vertical stators made of redwood, 24-in. x 1-1/2-in. x 1/2-in., attached to the side of the tank. The detention times at 5.5 gpm were 7 minutes in the first flocculation chamber and 9 minutes in the second. The motor-driven paddles in these tanks could be operated at various speeds to provide different degrees of mixing.

The up-flow clarifier designed for this project was a 400-gal. capacity, shop fabricated, steel cylindrical tank, 3-ft 9-in. in diameter with a 4-ft high straight section and a 60° cone bottom. Flocculated water entered a central 8-in. diameter chimney, discharged at a depth of about 4-ft below the surface, then flowed upward to the overflow trough at the surface. The detention time at 5.5 gpm was approximately 1 hour. The product water from the clarifier flowed to the dual-media filter, which consisted of 9-in. of anthracite coal (effective size 0.59 mm) over 9-in. of filter sand (effective size 0.62 mm) supported on gravel with a pipe underdrain. Filtered water was pumped to a 250-gal. reservoir to provide feed to the pumps for the carbon column systems.

Sludge was pumped from the clarifier by a positive pressure pump attached to the bottom of the cone and operated by a cycle timer to remove and discard sludge at predetermined intervals. Usually, this pump was operated for 1 minute at a time, three times per hour to discharge about 15-gal. per hour of sludge.

Carbon Adsorption Systems

The carbon adsorbers were vertical columns constructed of internally coated 10-in. diameter steel pipe as shown schematically in Figure 4. Each column was charged with 85 pounds of 12 x 40 granular activated carbon* which provided a 6-ft deep bed of settled carbon. The carbon was supported on a 6-in. layer of gravel and coarse sand over an inverted 5-in. diameter cone-shaped distributor. The columns designed for packed bed operation were 9-ft tall to allow a backwashing and disengaging zone. Those designed for expanded bed operation were 12-ft tall including at the top a 1-ft section of 11-in. i.d. transparent pipe to permit observation of the effluent from

*Pittsburgh CAL activated carbon, Calgon Corp., Pittsburgh, Pennsylvania.

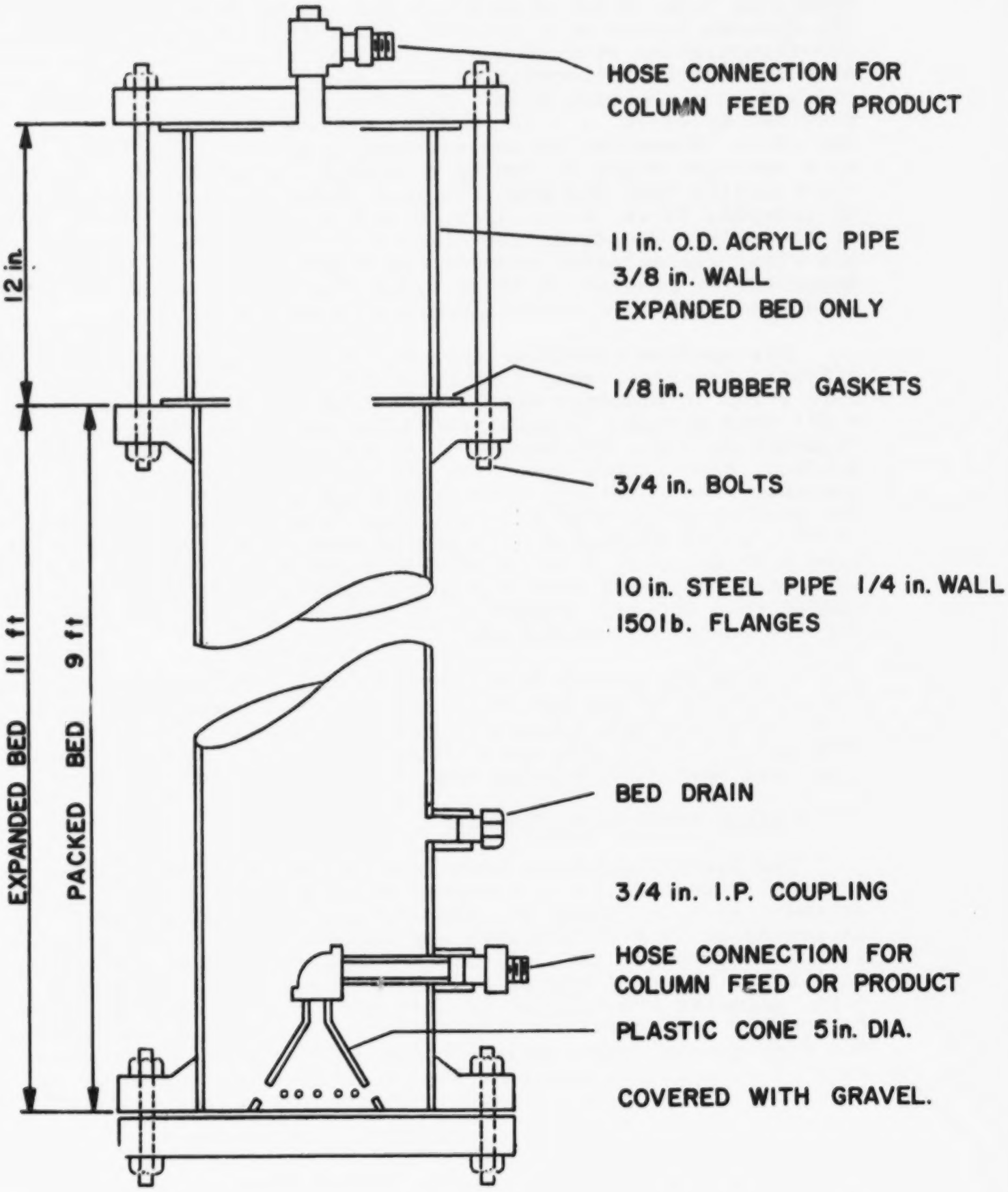

FIGURE 4 PILOT ADSORBER COLUMN DETAIL

the expanded carbon beds and to provide a visual check to insure that carbon was not being washed out of the column. Hose connections were provided at the top and the bottom of the columns.

The behavior of the 12 x 40 carbon in an expanded bed in the column at 5 gpm/ft^2 is shown in Figure 5.

Four constant displacement pumps driven by electric motors through variable speed drives were installed so that feed could be supplied to as many as four carbon adsorber systems. Reinforced rubber hose, 5/8-in. i.d., was used for the connecting lines to and between the columns to provide for ease of installation and rearrangement. All of the flow controls, including in-line valves, pressure gauges, flow meters (water meters), and solenoid sampling valves were mounted on one central operating panel within the building. Stream flows were maintained at constant rate by adjustment of the pump drives. The treated water from the expanded-bed columns was discharged into a drum so that any carbon particles carried out could be collected and returned to the column if necessary. All product water was returned to the sewage treatment plant.

The entire system was designed for essentially automatic operation. A technician visited the plant daily to take samples, adjust flows and perform any routine maintenance required.

Twenty-four hour composite samples of the primary effluent feed to each carbon column and the product water from each were collected automatically. Timer-controlled solenoid valves opened at 20-minute intervals to draw 100-ml samples. When composite samples were collected for periods longer than one day, appropriate adjustments were made either in the time the valve was open or in the interval between samples. These samples were composited in 5-gal. polyethylene bottles in an acid medium to maintain stability and prevent deterioration or biological activity over the sampling periods. Spot samples were collected by hand.

Chemical and biochemical analyses were performed at the FMC Chemical Research Center. Analytical determinations on composited samples included TOC, SOC, and SS. BOD, turbidity, phosphates and nitrates were run on spot samples brought unacidified to the laboratory for immediate analysis. Analytical procedures are discussed later in this Section.

The packed beds required frequent backwashing to dislodge the collected solids that caused buildup of pressure drop. The most effective procedure found for cleaning the carbon beds consisted of lowering the water level, injecting air into the bottom of the column for 5 to 10 min. and then backflushing with clean water to sweep away the dislodged solids. The sludge resulting from the carbon cleaning operation was collected in a drum so that any activated carbon lost from a column could be returned to that column.

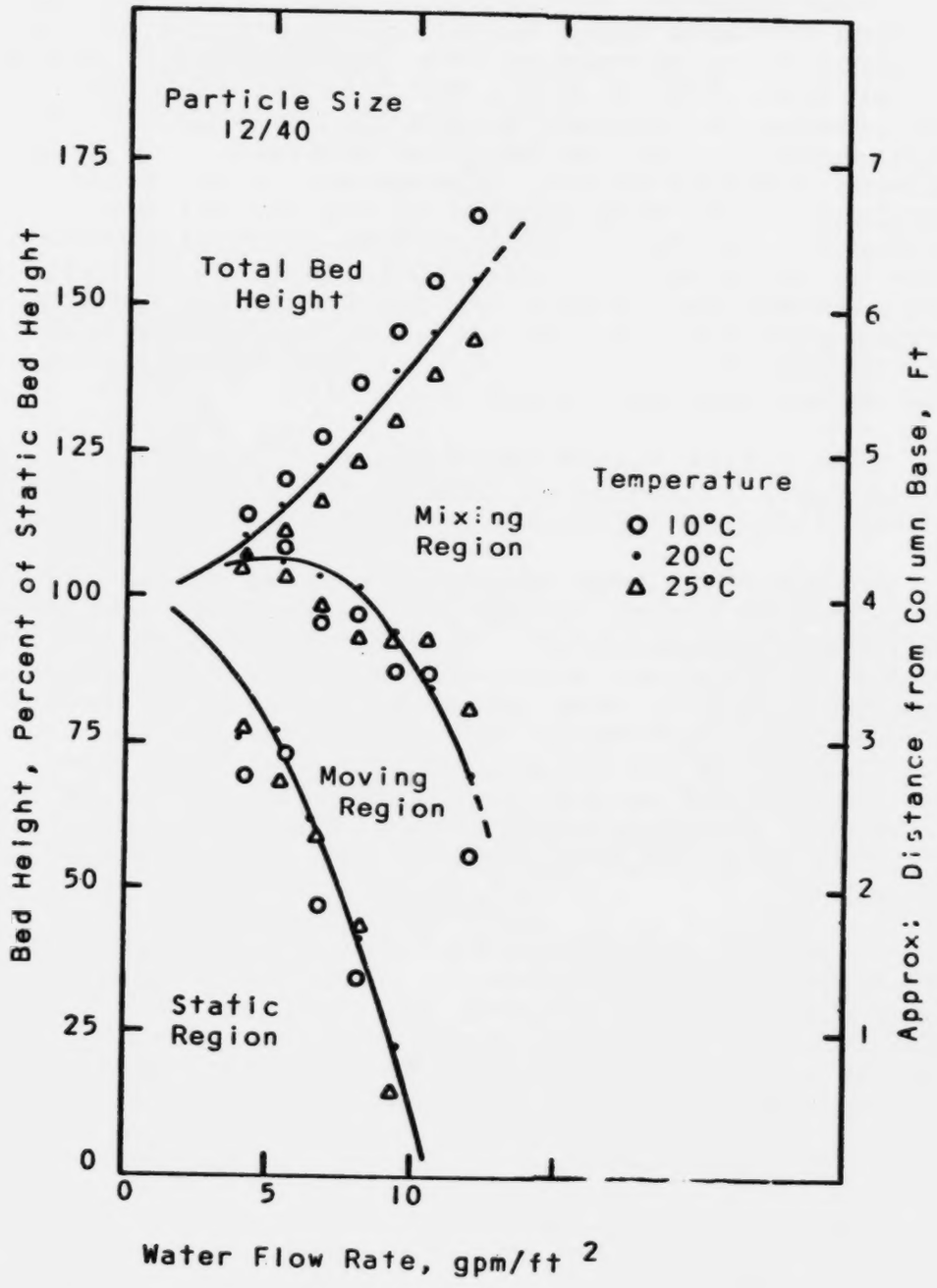

FIGURE 5 BEHAVIOR OF EXPANDED BEDS OF ACTIVATED CARBON

Phase-One Operation: Pre-Clarification

Parallel studies under the first phase of the experimental program examined the relative effectiveness of treating primary effluent by activated carbon with and without pre-clarification. These studies were conducted at the pilot plant facility over an operating period of approximately 75 days. Four adsorption systems were used; two systems operating on unclarified primary effluent and two on chemically clarified effluent, as shown in Figure 6. Each carbon system contained a 12-ft depth of activated carbon, 6-ft in each of two columns.

Two systems were operated in expanded-bed mode, while the other two systems were operated in packed-bed mode. Each system treated approximately 3600 gal. of primary effluent per day, corresponding to a carbon column loading of approximately 5 gpm/ft^2 of column cross section area.

The rate of flow to the expanded-bed and packed-bed systems operating on primary effluent was increased to 7 gpm/ft^2 for the final part of this experiment.

Phase-Two Operation: Extended Treatment

In the second phase of the program, chemically clarified primary effluent was treated in expanded-bed and packed-bed adsorbers for an extended period of continuous operation of 125 days. The carbon columns were arranged in two sets, each set with four columns in series to provide 24-ft of activated carbon in the systems, as shown in Figure 7. For this test fresh 12 x 40 activated carbon was charged to each column, and clarified effluent was pumped to the carbon beds at about 5 gpm/ft^2, or about 3600 gallons per day to each system. The expanded-bed and packed-bed systems had each treated about 450,000 gallons of clarified primary effluent when the run was terminated to allow time for Phase Three experiments.

Phase-Three Operation: Post-Clarification

At the conclusion of the 125 day run with clarified primary effluent, the two four-column adsorption systems still containing the same carbon, were switched directly to primary effluent and operated for an additional 30 days. During this period, post-clarification was studied in the laboratory and by feeding the adsorber effluent to the chemical clarification unit.

Particle Size Studies

Two parallel glass columns, 6-in. diameter x 9-ft tall, were charged with 4-ft settled depths of an experimental activated carbon of widely different particle size ranges. These columns were operated in expanded mode with clarified primary effluent as feed.

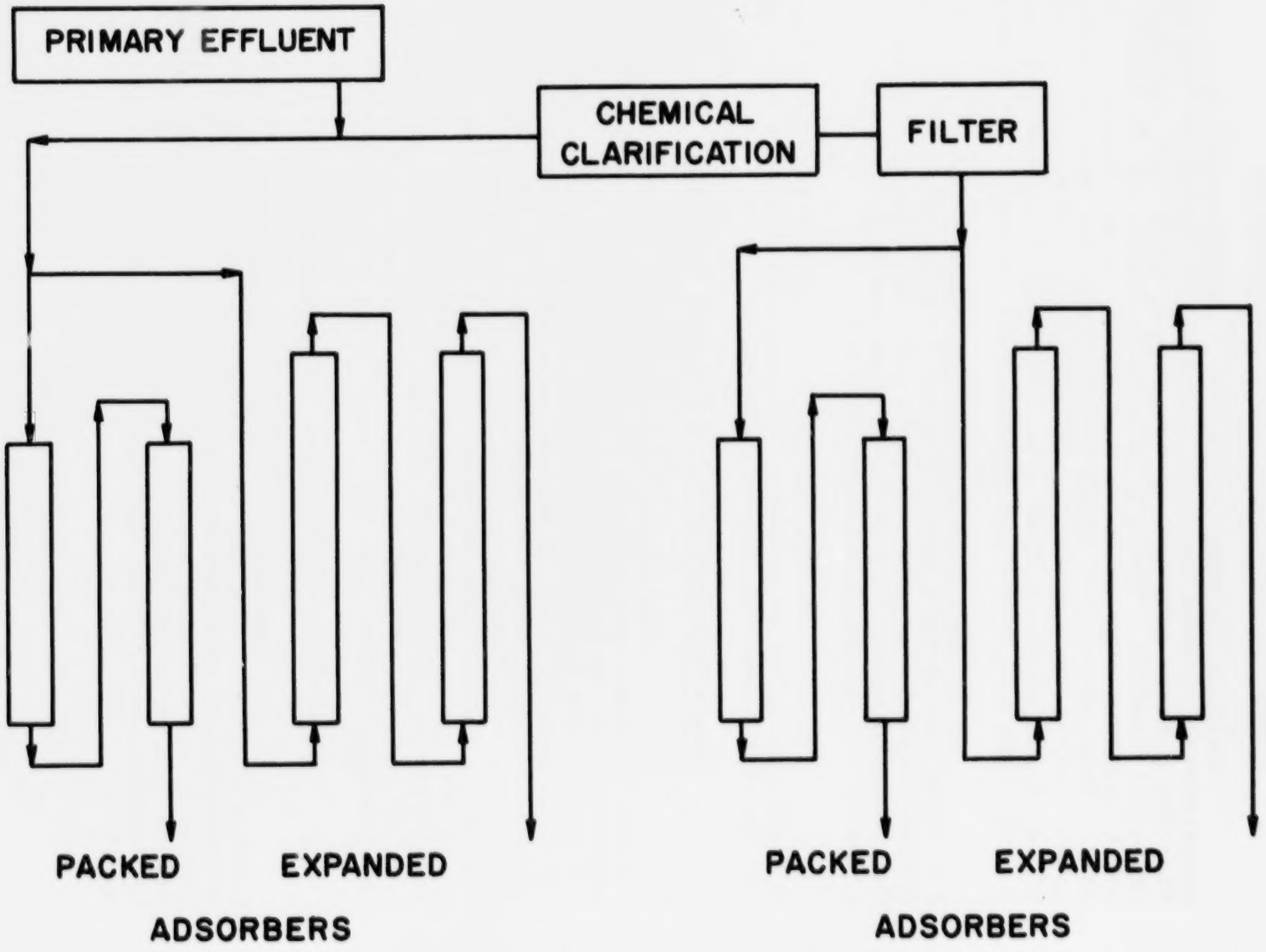

FIGURE 6 EXPERIMENTAL SET-UP FOR 12-FT CARBON BEDS

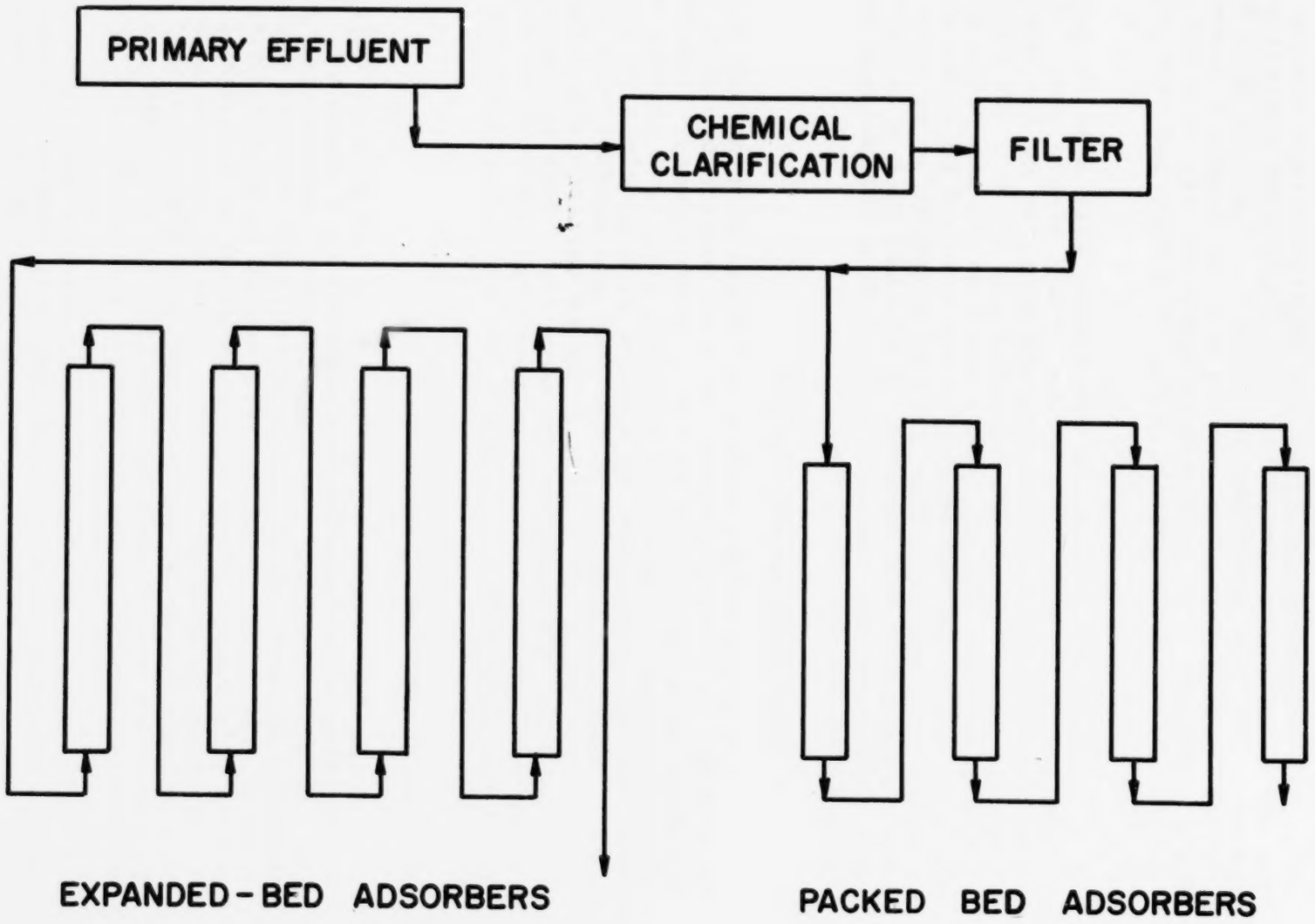

FIGURE 7 EXPERIMENTAL SET-UP FOR 24-FT CARBON BEDS

To prepare the carbon in the two particle size ranges studied, a batch of experimental activated carbon was passed through a screening apparatus and separated into several fractions. The two fractions selected for this experiment nominally 8 x 16 and 50 x 100, are described in Table I. Particle size 8 x 16 includes mostly particles passing a U. S. Standard Sieve No. 8 and retained by a U. S. Standard Sieve No. 16; 50 x 100 particles include mostly those passing a No. 50 sieve, and retained by a No. 100 sieve.

Separate rotameters and valves were used to regulate the feed rate to each test column from a single pump. The flow rate used for both columns was dictated by the maximum rate that would retain the expanded bed of 50 x 100 carbon in the adsorption column. With the 9-ft column and a settled depth of 4-ft, the bed expansion was limited to 100%, which was obtained at a specific flow rate of 1 gpm/ft^2. At this flow rate no expansion was observed in the bed of 8 x 16 particles. Spot samples of the feed and product from the columns were taken daily for TOC analyses.

Polishing Column Studies

A glass column with 1-in^2 cross section was filled to a depth of 1-ft with fresh 12 x 40 activated carbon and operated in a packed-bed mode with product water from the 24-ft expanded bed adsorber treating clarified primary effluent. Feed rate was controlled by a valve from an elevated supply tank. Composite samples of the feed and product were collected at frequent intervals during a day of testing, and preserved with acid for TOC analysis the next day. This polishing column concept was examined in four separate runs on four different days with fresh carbon in the test column for each run.

ANALYTICAL METHODS

Suspended solids concentration of the primary effluent and treated water samples was measured by a procedure[8] involving the use of 0.45-micron membrane filters. Before use, the membrane filters, which in manufacture are treated with an organic conditioning agent, were washed in distilled water to remove this agent. They were then dried in individual desiccators to constant weight. After filtration of a sample, each filter was dried again in the same desiccator and weighed to determine weight gain by retention of suspended solids. The filtrates were collected to provide samples for SOC analyses.

The Beckman Carbonaceous Analyzer was used for organic carbon analysis on well-mixed composite samples, directly for TOC, and, after filtration through the membrane filters, for SOC.

TABLE 1

Properties of Activated Carbons Used in The Studies of The Effect of Particle Size on Adsorption of Organics From Clarified Primary Effluents

Carbon Designation	8 x 16		50 x 100	
Sieve Analysis,	U.S. No.	%	U.S. No.	%
% Retained	8	0.0	40	0.4
	10	0.8	50	0.6
	12	7.4	80	57.8
	16	67.2	100	22.0
	20	16.0	140	16.8
	pan	8.6	pan	2.4
Average Particle Size, mm		1.4		0.2
Bed Expansion,	Rate	%	Rate	%
% of Settled Depth at Rates in gpm/ft^2	0.45	0	0.45	45
	0.95	0	0.95	100
	2.7	1		
	5.0	2		
Adsorptive Properties,				
Iodine No. mg/g		507		605
Methylene Blue mg/g		110		160

Determination of BOD of unacidified spot samples was performed by the dilution procedure described in Standard Methods.[9]

All turbidity determinations were made with a Hach Model 2100 Photoelectric Turbidimeter.

Total phosphate was determined by ASTM Procedure D515-60T- on samples after digestion to convert all phosphate to the ortho form.[10]

Nitrate was determined by ASTM Procedure D992-52.- Ammonia and organic nitrogen were determined by Kjeldahl Procedure as outlined in Standard Methods.[9]

RESULTS

COAGULATION AND CLARIFICATION STUDIES

Coagulant Selection

The most effective reduction in the turbidity of the primary effluent obtained in the laboratory jar tests was generally from a value in excess of 30 Jackson Turbidity Unit (JTU) to a level of about 1.0 JTU. The dosage ranges for inorganic coagulants providing better than 90% turbidity removal for the several samples of primary effluent examined were:

Alum	-	200 to 300 mg/l as $Al_2(SO_4)_3 \cdot 18H_2O$
Ferric Chloride	-	200 to 350 mg/l as $FeCl_3 \cdot 6H_2O$
Lime		300 or more mg/l as $Ca(OH)_2$

These coagulant dosages were consistently effective for clarification of primary effluent samples collected on several different days, even though the samples of primary effluent analyzed during this period varied in pH from 7.2 to 8.8, and in alkalinity from 200 to 300 mg/l.

Ferric chloride and lime both produced rapidly settling, strong floc particles. These flocs were resistant to breakage during transfer and reformed rapidly after dispersion to settle and provide a clear supernatant. Ferric chloride produced a neutral water; lime a strongly alkaline water with a pH of 9.5 or more. Coagulation with alum was slower, required closer pH control, produced a more fragile floc, and did not produce as clear a supernatant. Combinations of lime with ferric chloride were found to be effective.

Several anionic, nonionic, and cationic organic polyelectrolytes were tested in doses ranging from 0.1 to 5 mg/l, but none was found to be particularly effective as a primary coagulant. As secondary floc strengtheners, used in combination with iron or alum, some of the polyelectrolytes produced larger floc particles which settled more rapidly than those formed with alum or iron alone. Turbidity removal was generally no better for the combination, however, and the dosage of primary coagulant could not be reduced much below that required when only the metal salt was used.

Ferric chloride used alone gave consistently good clarification and rapid settling of floc, and produced an essentially neutral clarified water with a pH from 6 to 7. For these reasons and also because of the relative ease of handling and feeding the small quantities required, ferric chloride was selected for use as the coagulant for the pilot-plant operations, although lime may well be preferred for larger scale operation.

Coagulation Conditions

The results of the tests for selection of optimum conditions for use of the ferric chloride coagulant may be summarized by the following observations:

- Initial rapid mix for a short period of time was found desirable for thorough dispersion of the reagent without adversely affecting the later steps.
- Extended high speed mixing restricted the growth of floc particles during subsequent flocculation under conditions of slow stirring.
- In the flocculation step, mixing at excessively high speeds (80 rpm) resulted in small, poorly settling floc particles; excessively low speeds (20 to 30 rpm) produced growth of larger particles which were less effective for turbidity removal.
- Moderate agitation (40 rpm) after a short rapid mix seemed most effective for good coagulation and turbidity removal by producing a large number of relatively small, dense floc particles.
- A final slower mixing (20 rpm) to permit flocculation of the particles formed during coagulation at moderate speed after an initial rapid mix, appeared to offer an advantage.

Design of Pilot Plant System

The pilot plant clarification system was designed to provide a series of mixing conditions similar to those found to give best results in the jar tests. To translate the laboratory scale stirring conditions to the pilot plant design, the degree of agitation was expressed in terms of the velocity gradient, G, which is a measure of energy dissipation in a mixing or stirring system.[11,12] Values for G were calculated for the conditions used in the jar test assuming a drag coefficient of 1.2 for metal blades, and water velocity equal to 3/4 of the paddle-tip radial velocity. Values for the velocity gradient calculated for paddle speeds up to 180 rpm ranged to 90 fps/ft, as illustrated in Figure 8, with values reported by Hudson[12] for comparison. While there were inconsistent results, the experiments which gave the best clarification were operated at values of G in the range of 10 to 20 fps/ft.

The velocity gradient in the rapid mix section of the pilot plant system cannot be estimated accurately, but to approach the high velocity required, a combination of jet mixing action and the propeller recirculation was used. Values

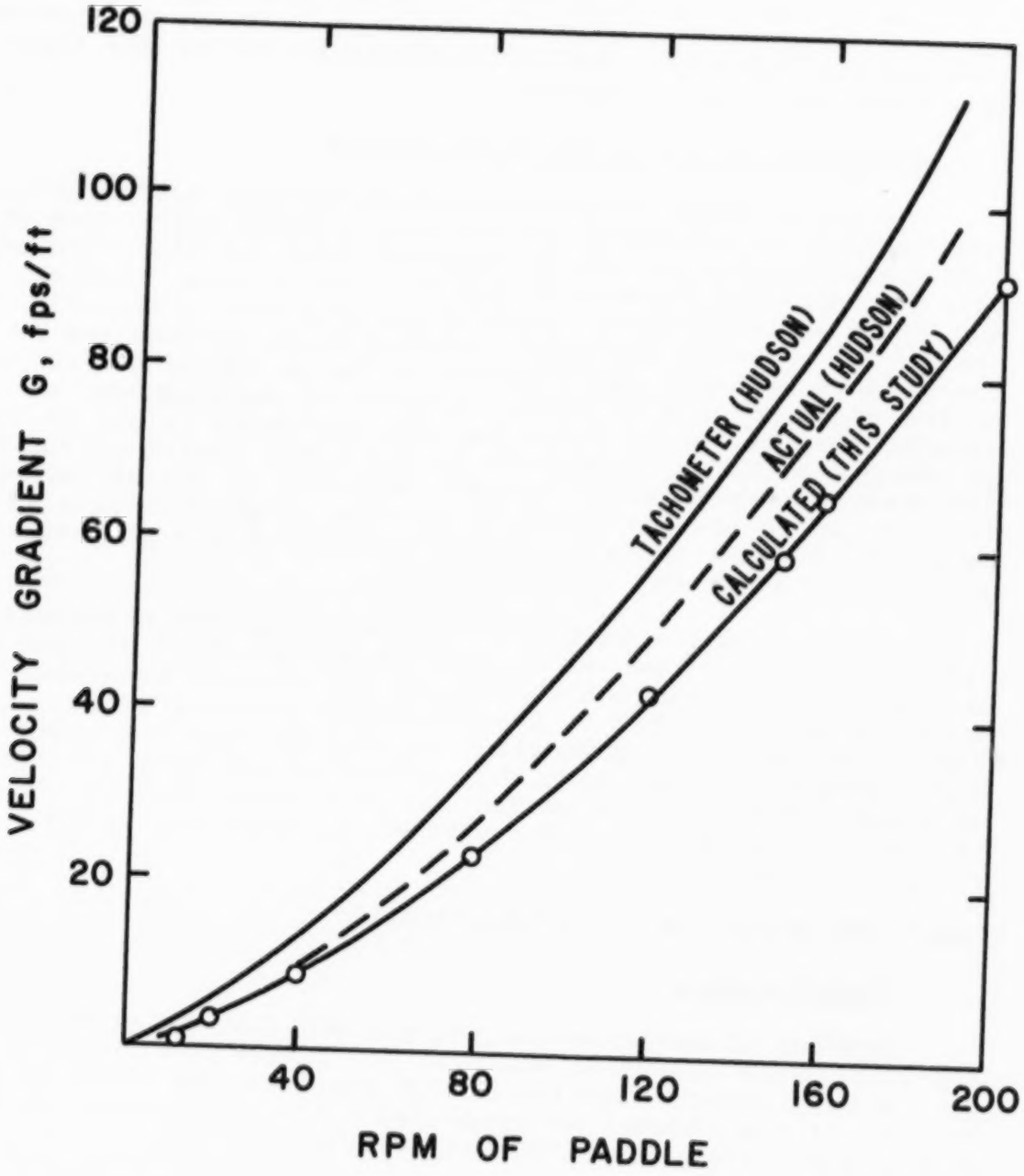

FIGURE 8 VELOCITY GRADIENT vs. PADDLE RPM IN JAR TEST APPARATUS

for the velocity gradient were calculated for the pilot plant coagulation system assuming a drag coefficient of 1.8 for the wooden paddles and a water velocity equal to 3/4 of the radial velocity at the center of the paddles. Figure 9 shows the relationship between paddle rate and the calculated values for G. The system was operated continuously at 18 rpm for the entire experimental period.

The up-flow clarifier for the pilot plant system was designed to provide a settling period of at least 30 minutes with minimum agitation and effective retention of the floc in a floating sludge blanket.

Operation of the Pilot Plant System

The pilot scale coagulation-clarification system provided good removal of suspended solids over a large percentage of the operating periods, as may be observed from the clarified effluent data presented in Figures 10 and 11. There were, however, during the Phase-One experiment, certain periods when coagulation with the ferric chloride was poor. During these periods the pH of the primary effluent was observed to be as low as 6.6 compared to the usual pH of 8 or more. Alkalinity measurements on several samples during these periods indicated values as low as 100 ppm as $CaCO_3$, compared to the usual levels of 200 to 300 observed during other times. Addition of sodium carbonate in solution to the mix tanks to provide an additional alkalinity of about 100 mg/l as $CaCO_3$ during periods of low pH restored good flocculation and clarification.

Further results on the effectiveness of the coagulation-clarification for removal of organic matter (TOC, SOC and BOD) and phosphate within the context of the overall treatment sequence are presented in the following sections of this report. These results may be summarized by stating that the chemical clarification system was highly effective not only for removal of suspended matter and production of a clear feed to the carbon columns, but also for removal of dissolved organic matter and phosphates.

PHASE-ONE OPERATION: PRECLARIFICATION

Clarification

Results of analyses for TOC and SOC for the primary effluent and chemically clarified effluent are given in Figures 12 and 13. A consistent reduction of TOC resulted, as might be expected because of the removal of suspended matter. However, in addition, a consistent removal of SOC was observed.

The weights of TOC and SOC removed in the clarification system, presented in Table 2, were calculated from the volumes treated and the analyses of the feed streams to the carbon

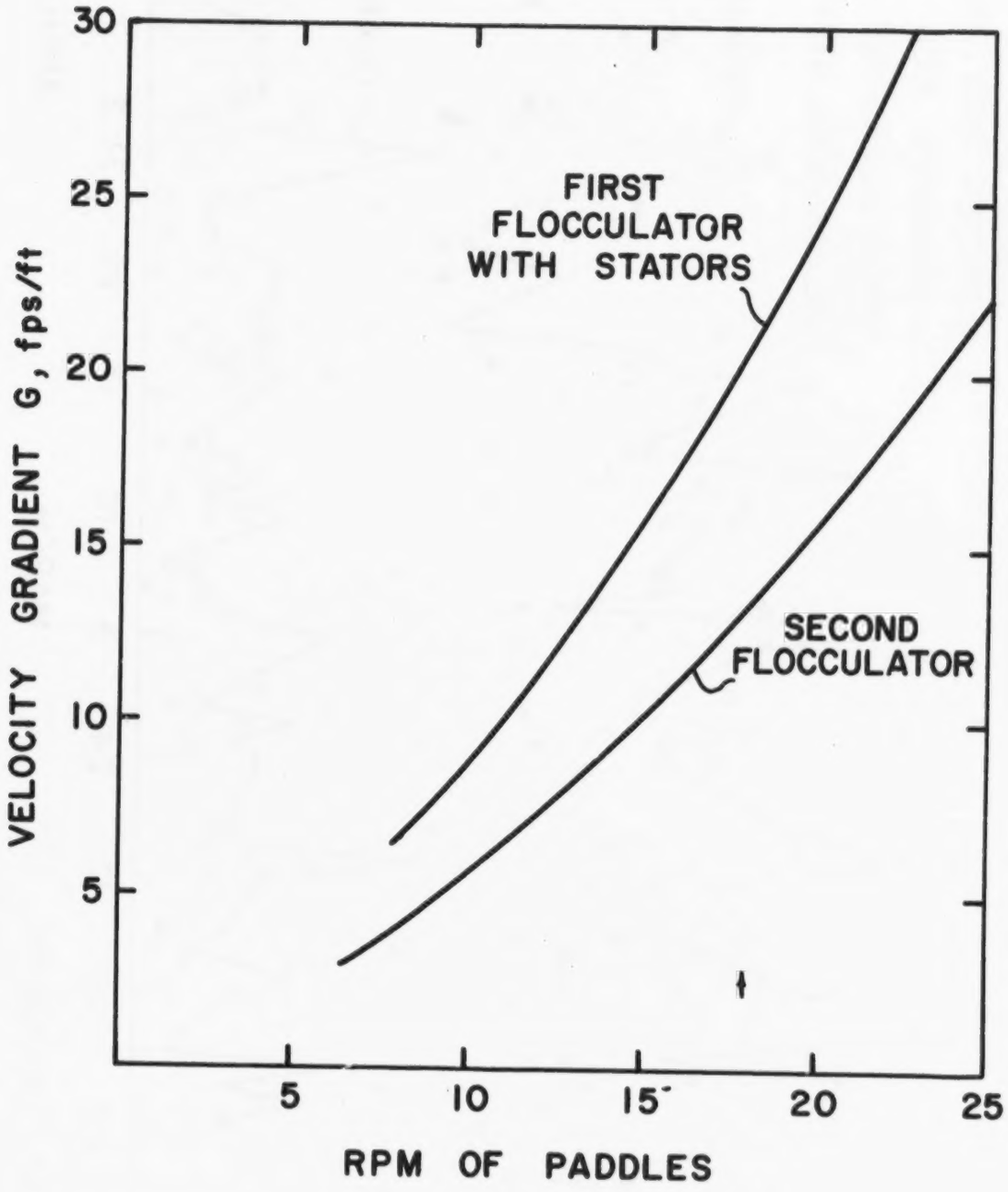

FIGURE 9 VELOCITY GRADIENT vs. PADDLE RPM FOR DRUM FLOCCULATORS

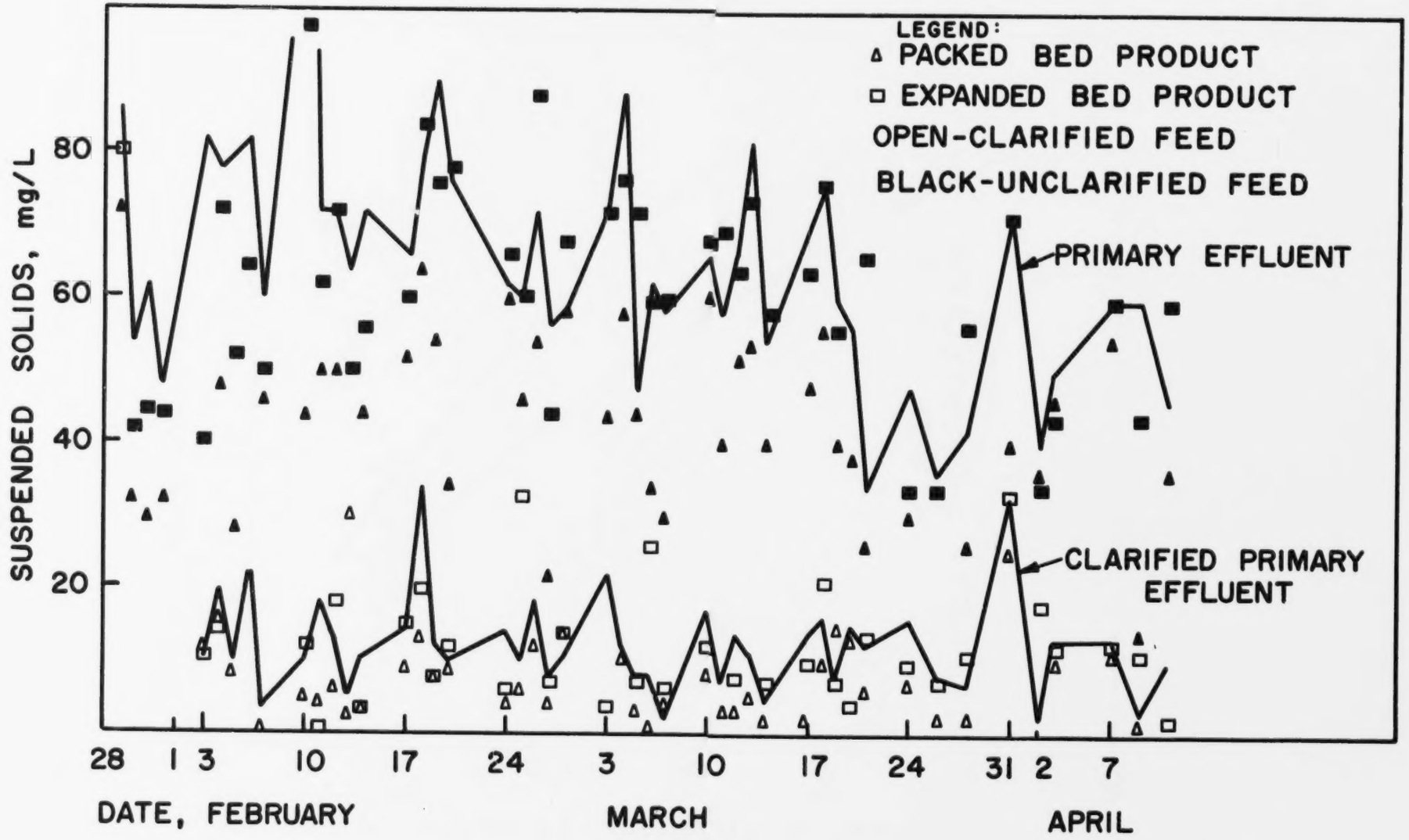

FIGURE 10 REMOVAL OF SUSPENDED SOLIDS FROM PRIMARY EFFLUENT BY CLARIFICATION AND ACTIVATED CARBON BEDS

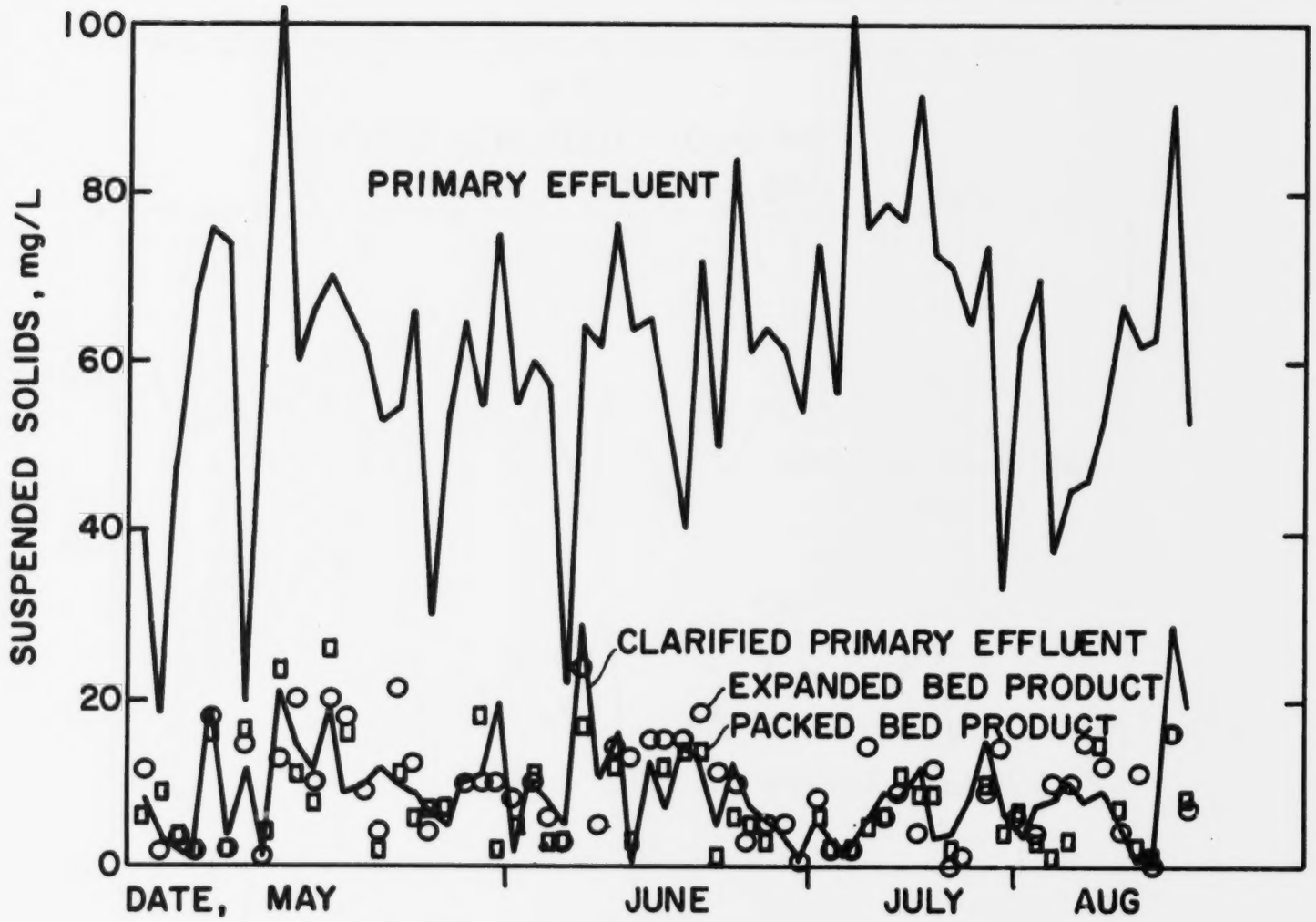

FIGURE 11 REMOVAL OF SUSPENDED SOLIDS FROM PRIMARY EFFLUENT BY CHEMICAL CLARIFICATION AND ACTIVATED CARBON BEDS

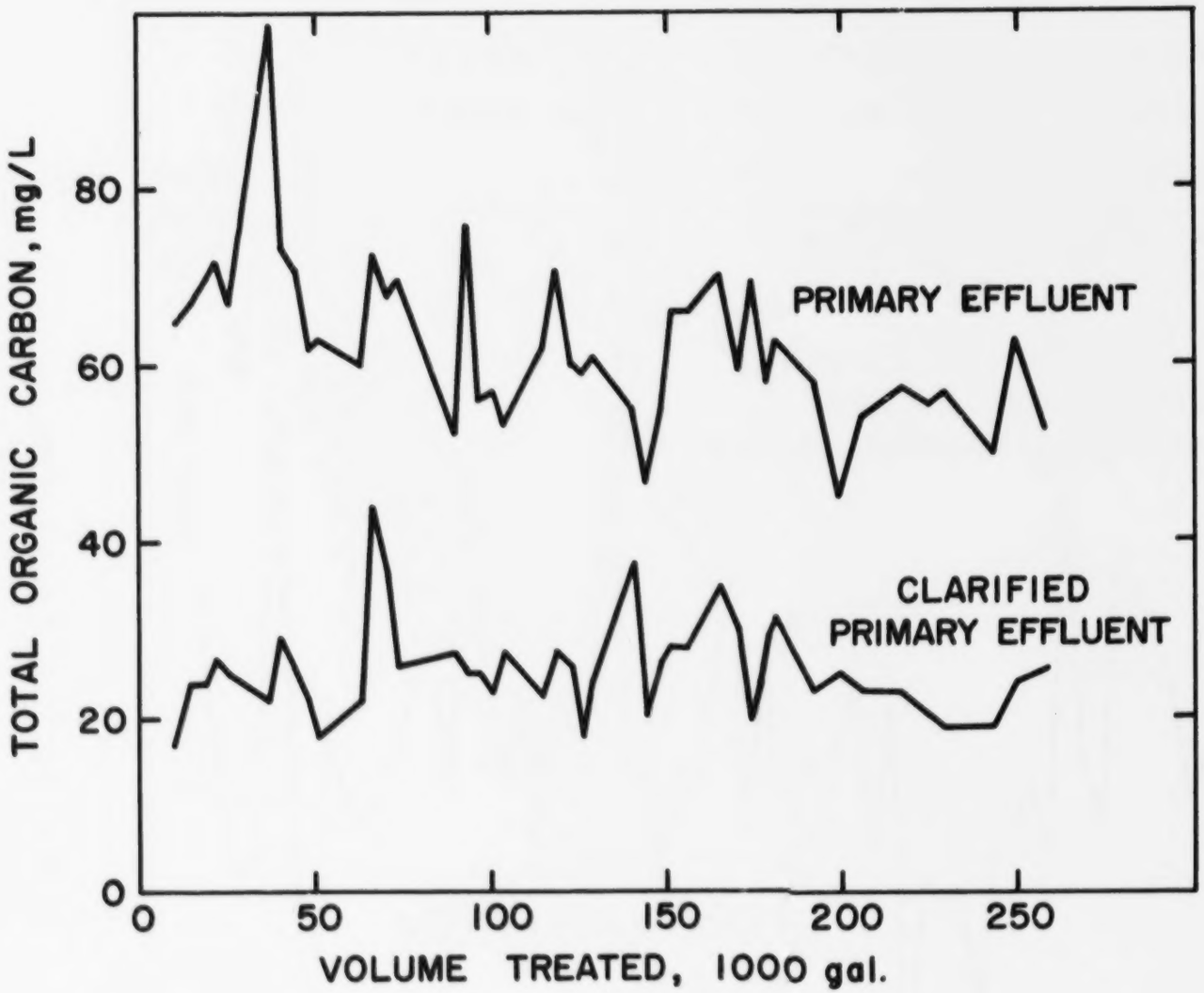

FIGURE 12 REMOVAL OF TOTAL ORGANIC CARBON FROM PRIMARY EFFLUENT BY FERRIC CHLORIDE COAGULATION-CLARIFICATION

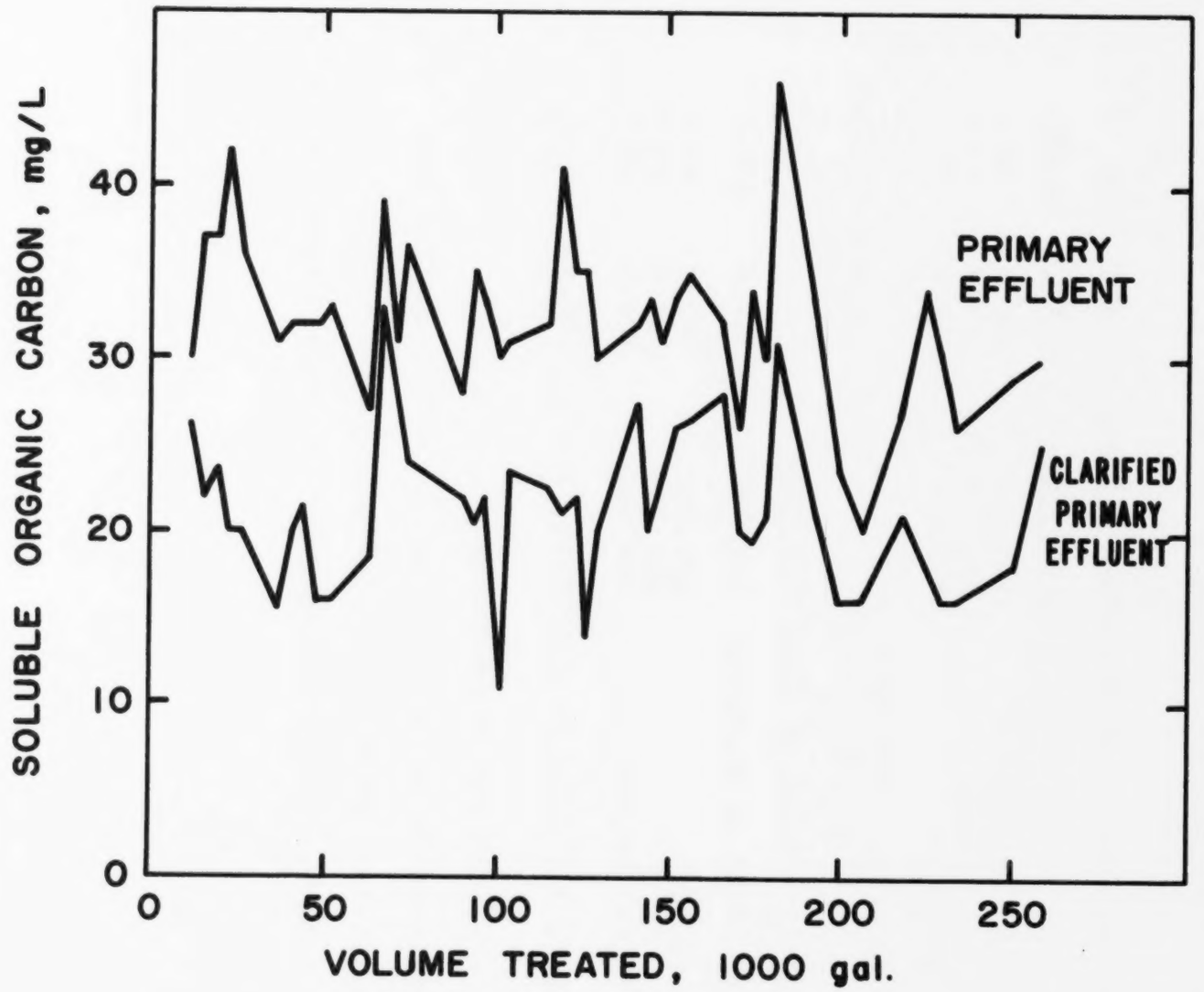

FIGURE 13 REMOVAL OF SOLUBLE ORGANIC CARBON FROM PRIMARY EFFLUENT BY FERRIC CHLORIDE COAGULATION-CLARIFICATION

TABLE 2

TOC and SOC Content of Primary Effluent and Clarified Primary Effluent Feeds to Columns and Effect of Coagulation With Ferric Chloride: Phase One Pilot Operation

Period - January 27 to April 11, 1969

	Volume, Gal.	lb TOC	lb SOC
Organic Content of Untreated Primary Effluent Feed			
Feed to PCU*	296,275	150.0	76.6
ECU	321,612	162.4	82.8
Total	617,887	317.4	159.4
In Primary Effluent lb/1000 gal.		0.514	0.258
Organic Content of Clarified Feed			
Net Feed to Clarifier	510,068	262.0	131.6
To PCC	252,484	52.8	44.9
ECC	257,584	53.8	45.6
Total Product	510,068	106.6	90.5
Organics Removed by Clarifier, lb		155.4	41.1
%		59.3	31.2

Note - ∿10% Wasted as Sludge

Ferric Chloride used = 666 lb = 1.3 lb/1000 gal. = 156 mg/l

*Activated Carbon Column Designations:

PC = Packed EC = Expanded U = Untreated Feed C = Clarified Feed

column systems. The average concentration of TOC was reduced from 60 to 25 mg/l, and SOC from 31 to 21.5 mg/l by clarification, which thus removed an average of 59.3% of the TOC and 31.2% of the SOC from the primary effluent.

Adsorption

The results of analyses for TOC and SOC on unclarified primary effluent and the treated water leaving both the expanded-bed and the packed-bed systems, are presented in Figures 14 and 15. The cumulative amounts of TOC and SOC charged to and removed by the systems are shown in Figure 16. In this plot, the slope of each line represents the fractional removal of organic carbon. During this operation, the expanded bed handled slightly more water than the packed bed due to the down time of the packed beds for column cleaning, which was necessary to remove accumulated suspended solids.

As noted previously, after approximately 2/3 of the 75 day operating period of this experiment had been completed the rate of primary effluent feed to the columns was increased from 5 gpm/ft^2 to about 7 gpm/ft^2. At the higher flow rate, the carbon beds continued to remove about the same proportion of TOC and SOC from the primary effluent.

At the termination of the run, the expanded bed had removed 33% and the packed bed 43% of the weight of TOC applied, and 38% and 40%, respectively, of the weight of SOC.

The results of TOC and SOC analyses from the parallel column systems operating on clarified primary effluent are shown in Figures 17 and 18. The cumulative amounts of organic matter charged to and removed by the carbon systems are given in Figure 19 for TOC and Figure 20 for SOC. The expanded and packed beds each removed over 50% of the weight of TOC and SOC charged during the 75 days of operation. A comparison of the values of TOC and SOC shows that most of the organics present in the clarified feed and column products consisted of SOC. At the time the test was terminated, both systems were still removing 45% of the SOC applied, as indicated in Figure 20.

Data for each of the four systems, presented in Table 3, show the total volume treated and the quantities of TOC and SOC removed during the period of this test. Average concentrations of TOC and SOC were calculated for the feed and the product for each of the systems, as was the organic loading on the activated carbon at the end of the experiment. The fraction of TOC and SOC removed from the clarified primary effluent by the carbon beds was greater than that removed from the unclarified primary effluent.

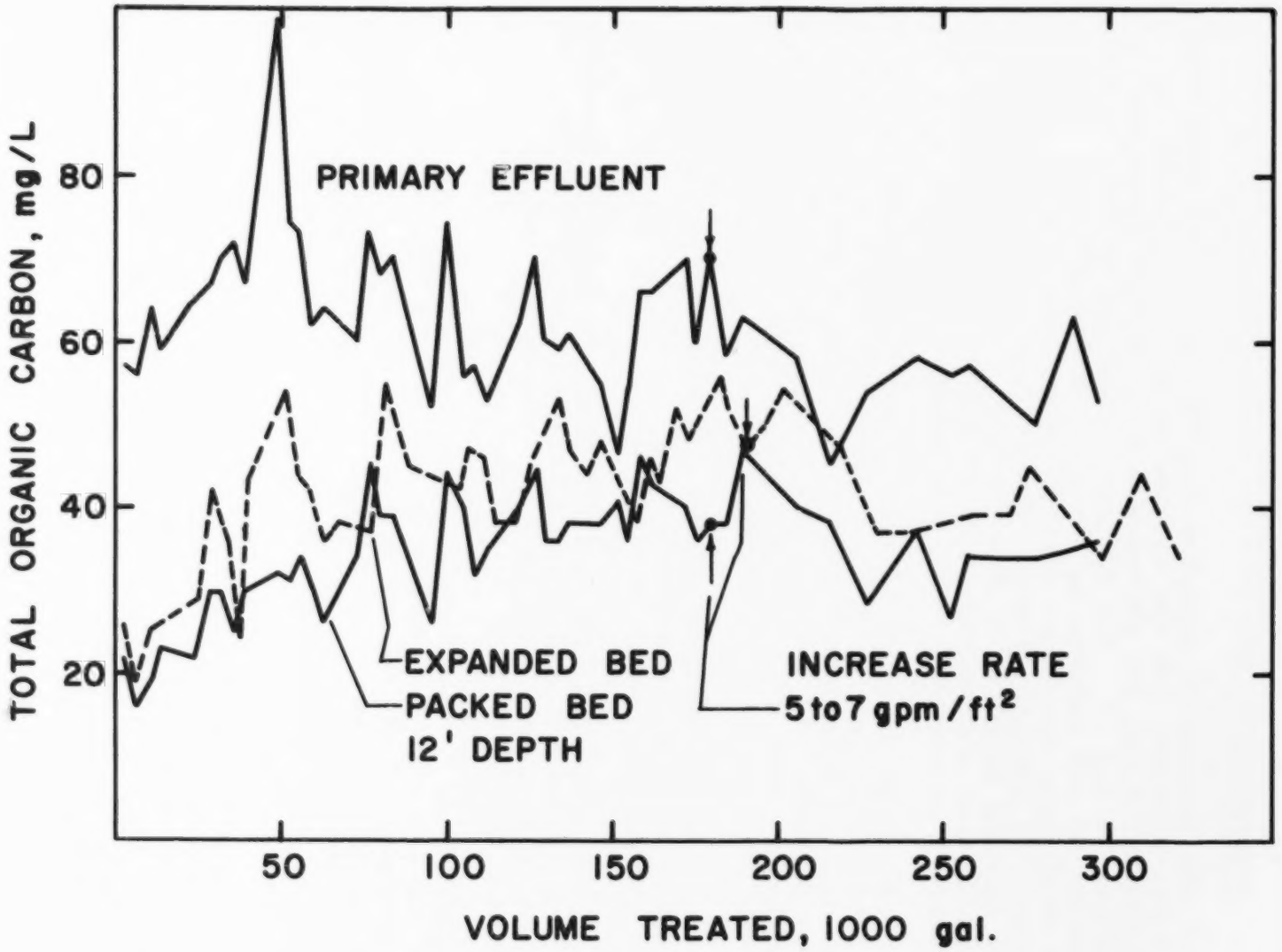

FIGURE 14 REMOVAL OF TOTAL ORGANIC CARBON FROM PRIMARY EFFLUENT IN BEDS OF ACTIVATED CARBON

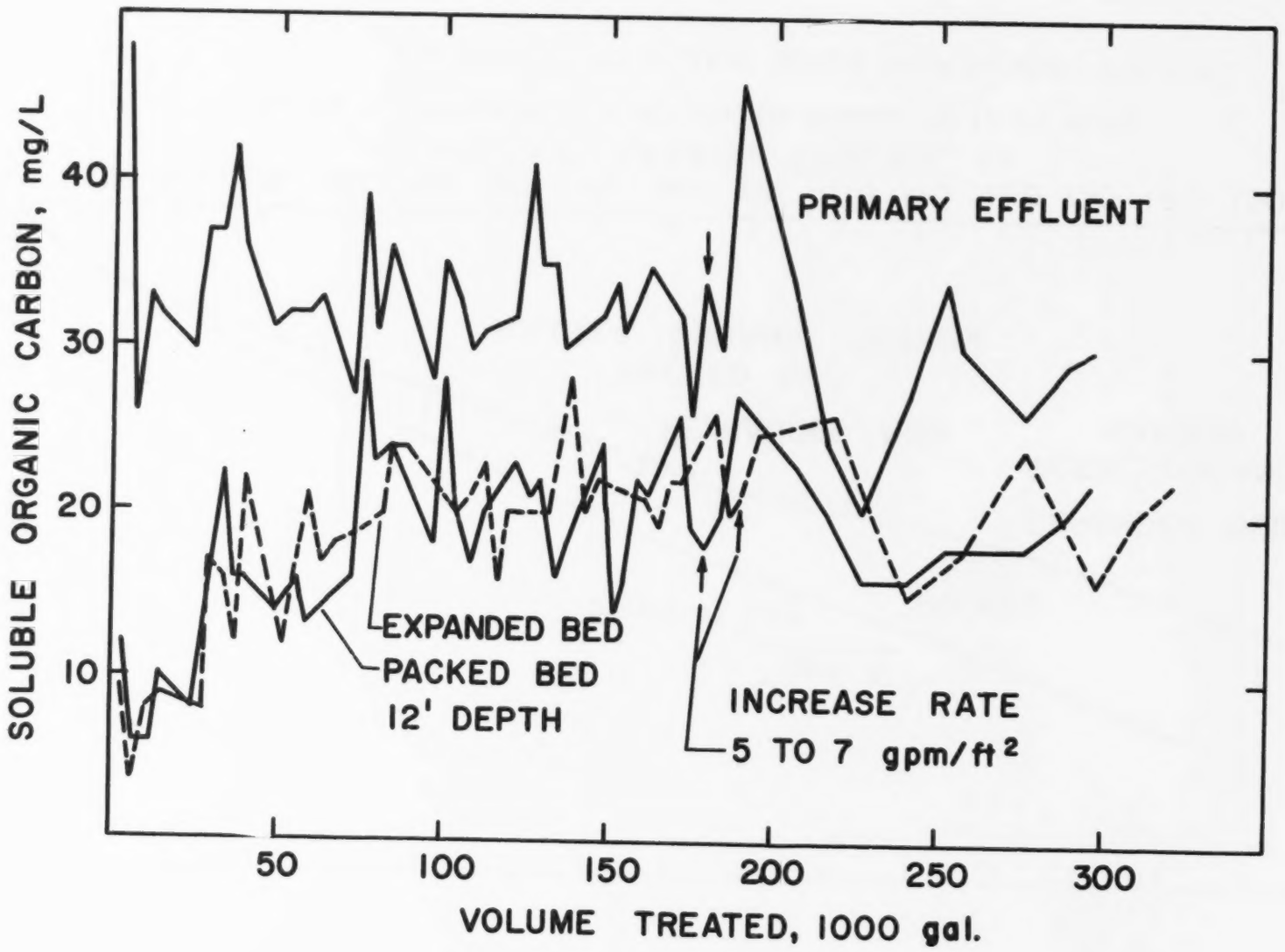

FIGURE 15 REMOVAL OF SOLUBLE ORGANIC CARBON FROM PRIMARY EFFLUENT IN BEDS OF ACTIVATED CARBON

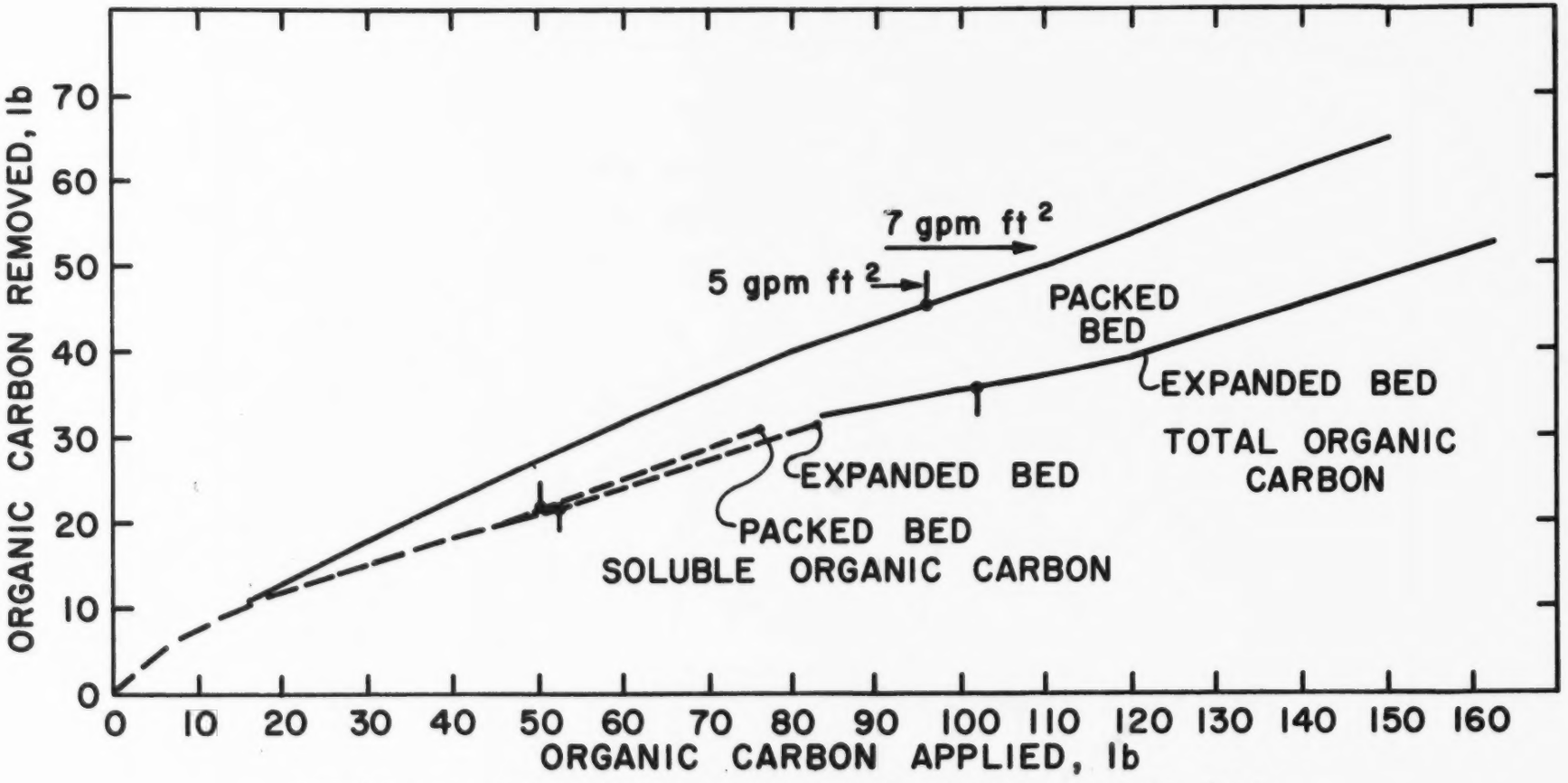

FIGURE 16 PERFORMANCE OF ACTIVATED CARBON IN 12-FT BEDS FOR REMOVAL OF ORGANIC CARBON FROM PRIMARY EFFLUENT

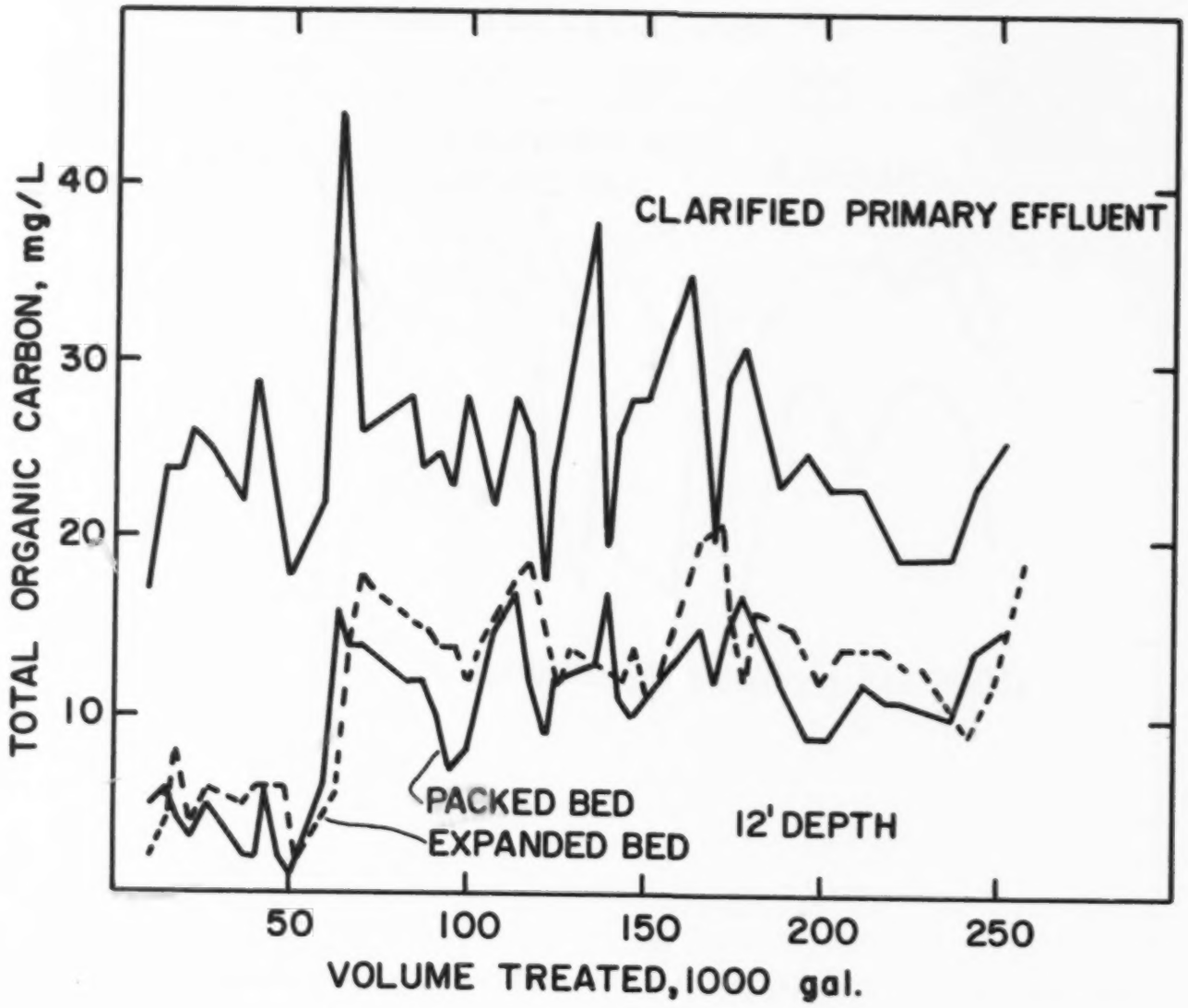

FIGURE 17 REMOVAL OF TOTAL ORGANIC CARBON FROM CLARIFIED PRIMARY EFFLUENT BY ACTIVATED CARBON

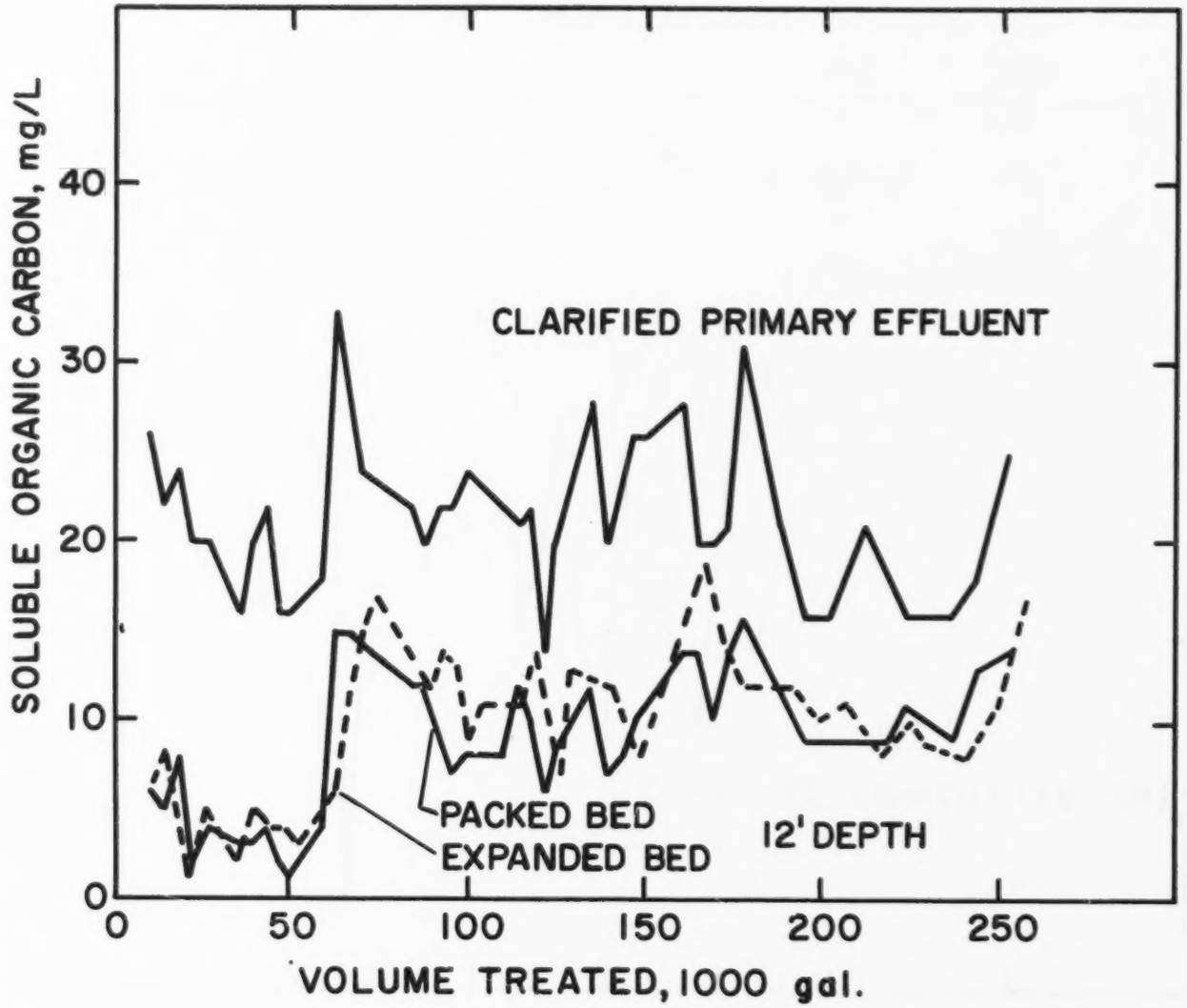

FIGURE 18 REMOVAL OF SOLUBLE ORGANIC FROM CLARIFIED PRIMARY EFFLUENT BY ACTIVATED CARBON

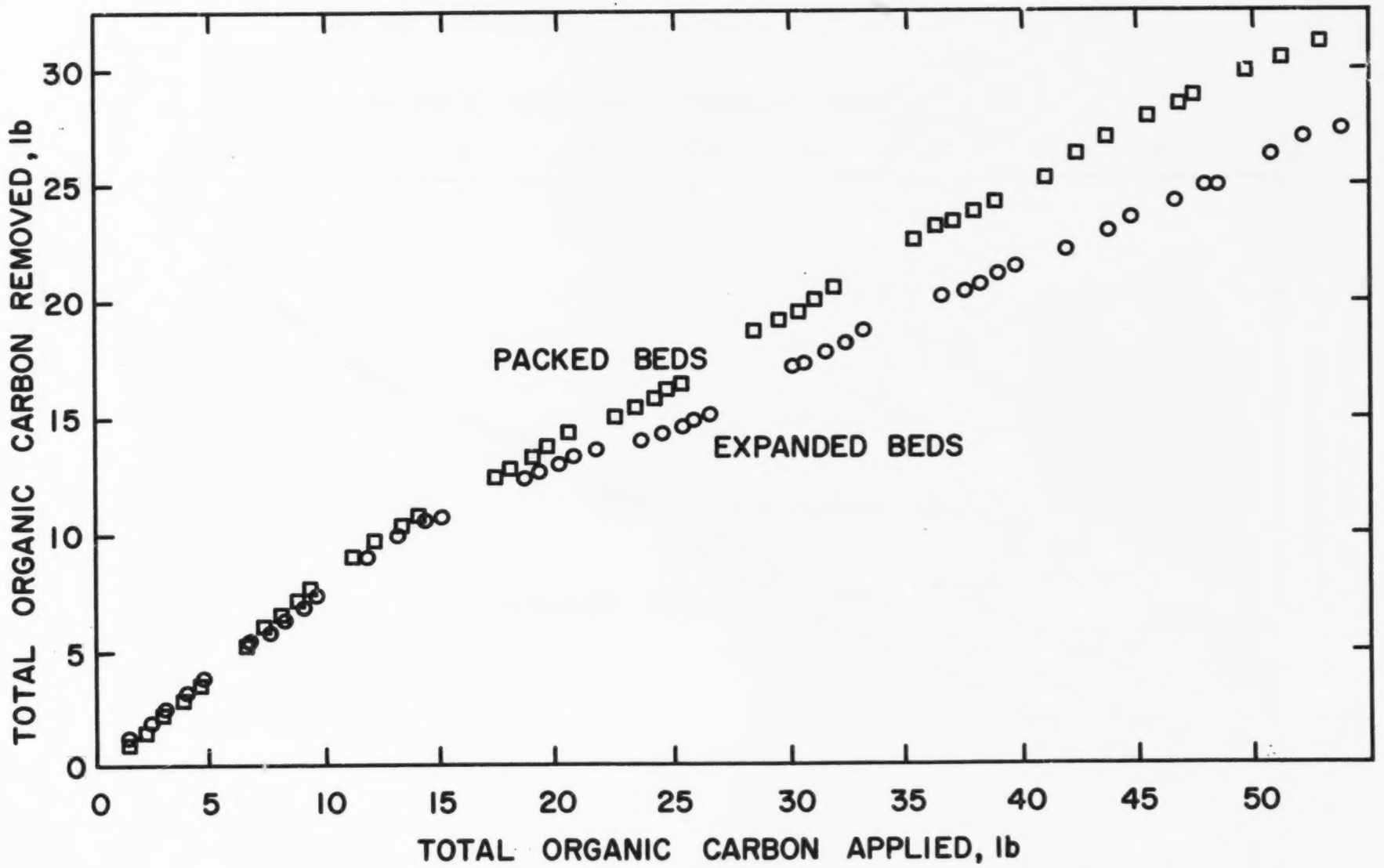

FIGURE 19 PERFORMANCE OF ACTIVATED CARBON IN 12-FT DEEP BEDS FOR REMOVAL OF TOTAL ORGANIC CARBON FROM CLARIFIED PRIMARY EFFLUENT

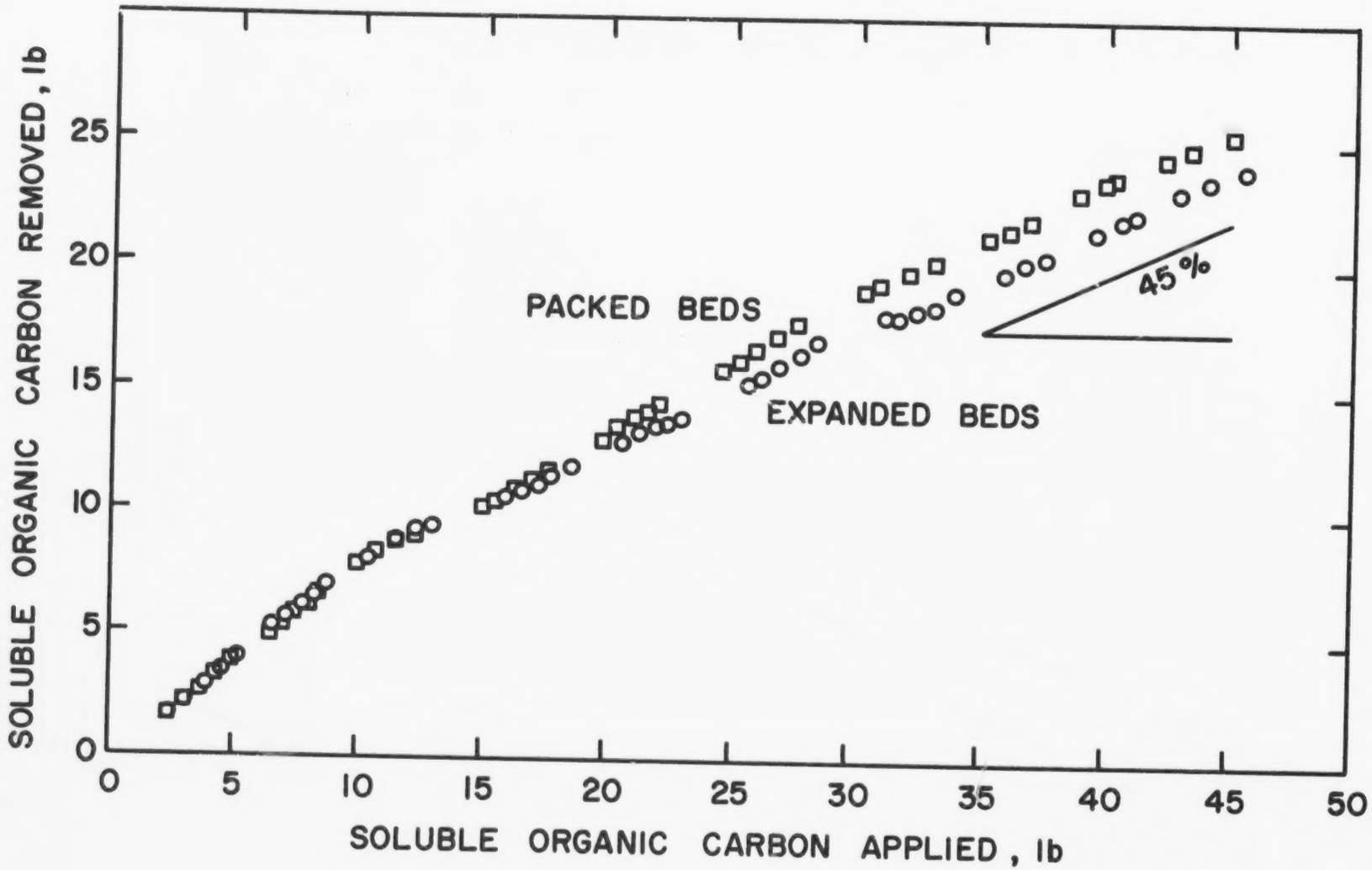

FIGURE 20 PERFORMANCE OF ACTIVATED CARBON IN 12-FT DEEP BEDS FOR REMOVAL OF SOLUBLE ORGANIC CARBON FROM CLARIFIED PRIMARY EFFLUENT

TABLE 3

Removal of TOC and SOC From Primary Effluent and Clarified Primary Effluent by Adsorption in 12-Ft Carbon Beds: Phase One Pilot Operation

Period - January 30 to April 11, 1969

COLUMN	PCU	ECU	PCC	ECC
FEED	Untreated		Clarified	
TOTAL VOLUME TREATED, gal.	296,275	321,612	252,484	257,584
Total Organic Carbon				
In Feed, lb	150.0	162.3	52.8	53.7
Prod.	84.7	109.8	21.6	26.3
Removed	65.3	52.5	31.2	27.4
Avg. Conc. Feed, mg/l	60.7	60.5	25.1	25.0
Prod.	34.3	40.9	10.2	12.2
Percent Removed	43.5	32.3	59.1	51.0
Soluble Organic Carbon				
In Feed, lb	76.6	82.8	44.9	45.6
Prod.	45.9	51.5	19.3	21.6
Removed	30.7	31.3	25.6	24.0
Avg. Conc. Feed	31.0	30.9	21.3	21.2
Prod.	18.6	19.2	9.2	10.0
Percent Removed	40.1	37.8	57.0	52.7
lb TOC per lb AC	0.38	0.31	0.18	0.16
lb SOC per lb AC	0.18	0.18	0.15	0.14

The results of five-day BOD determinations are given in Figure 21. Separate analyses indicated that the primary clarifier removed about 50% of the BOD from the raw sewage. The BOD of the primary effluent at the time the samples were taken varied from about 90 to 40 mg/l. The chemical clarification step consistently removed about 70% of the BOD from the primary effluent to produce a clear water with an average BOD of about 15 mg/l, varying from 5 to 29 mg/l, over the period of the run. The BOD of the clarified and carbon treated water ranged between 3 and 16 mg/l.

Samples were periodically analyzed for total phosphate. The results of these analyses are presented in Figure 22 with phosphate reported as PO_4^{-3} . As expected, the carbon bed alone removed little or no phosphate from the untreated primary effluent. With clarified primary effluent, the phosphate was lower after carbon adsorption in most cases, which suggests that some of the precipitated phosphate was carried out of the clarifier and trapped in the carbon bed. The clarification of primary effluent with ferric chloride usually reduced the phosphate to less than 5 mg/l from its initial concentration of from 15 to 40 mg/l.

Analyses for various forms of nitrogen were also conducted on the samples. While nitrate would not normally be expected to appear in significant concentration in raw sewage or primary effluent, several analyses indicated nitrate concentration of 5 to 15 mg/l, as NO_3^- in the ELSA primary effluent. The city water during this period was found by infrequent analyses to contain as much as 5 mg/l. Nitrate was only minimally affected by clarification but was removed essentially completely on passing through the carbon bed, probably by biological reduction. This removal of nitrate in the carbon beds was not observed on the first samples analyzed, when there was only fresh activated carbon in the system. In a few infrequent analyses for ammonia and organic nitrogen, it was found that neither coagulation nor carbon adsorption had any effect on the ammonia concentration of the primary effluent, which ranged from 20 to 50 mg/l. Organic nitrogen was reduced by clarification from about 4 to 7 mg/l in the primary effluent to 2 to 3 mg/l in the clarified effluent, and after carbon treatment to about 1 mg/l. These removals were in about the same proportion as the organic matter removals.

The composite samples collected from the operating systems were filtered to provide a measure of the suspended solids retained on membrane filters with effective openings of 0.45 microns. The results of these analyses were shown earlier in Figure 10. Clarification consistently reduced the suspended solid content to about 10 mg/l. The packed beds of activated carbon removed additicnal suspended solids, as expected. The expanded beds were also observed to remove some suspended solids from the primary effluent, possibly by collecting these

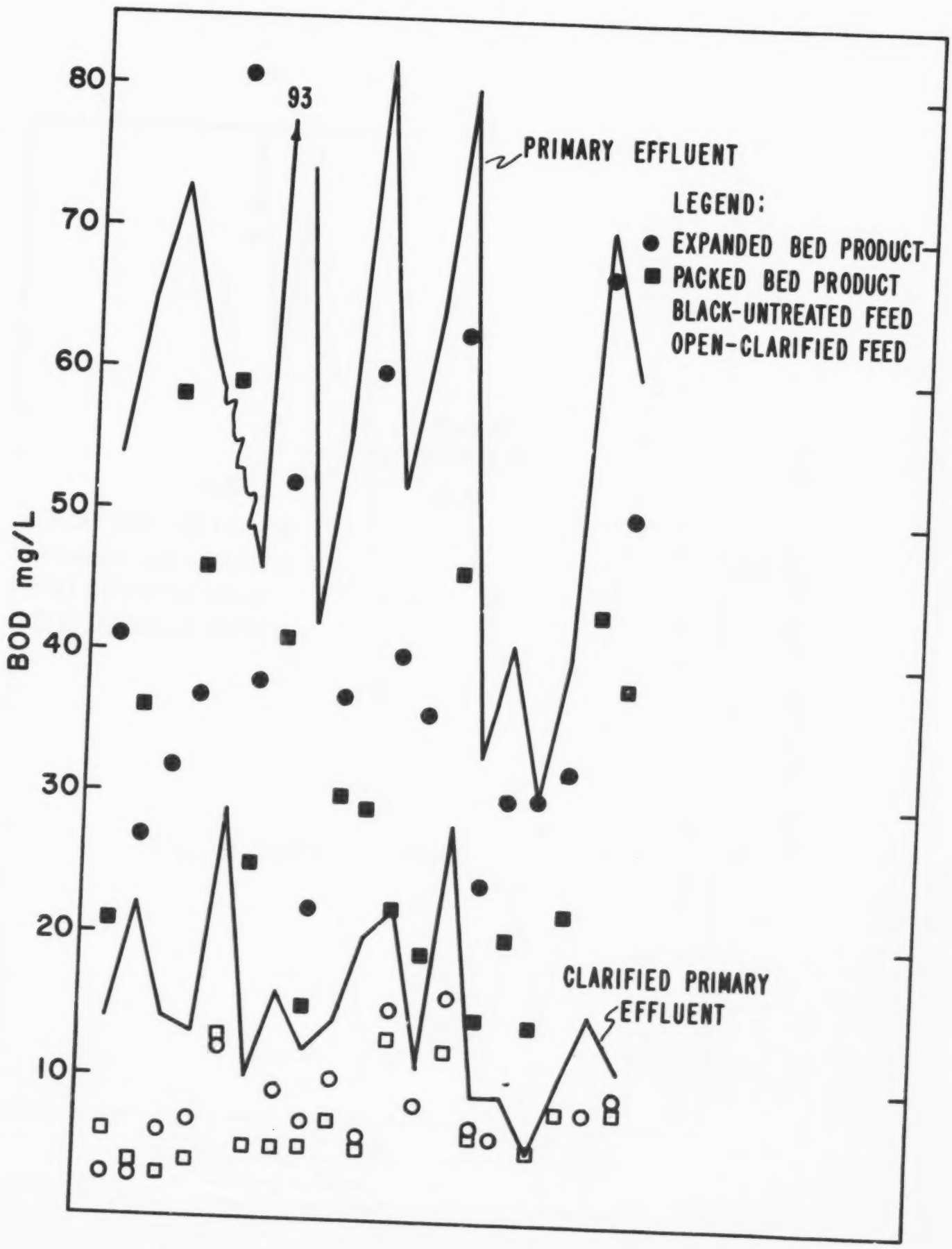

FIGURE 21 REMOVAL OF BOD FROM PRIMARY EFFLUENT BY CHEMICAL CLARIFICATION AND ACTIVATED CARBON BEDS

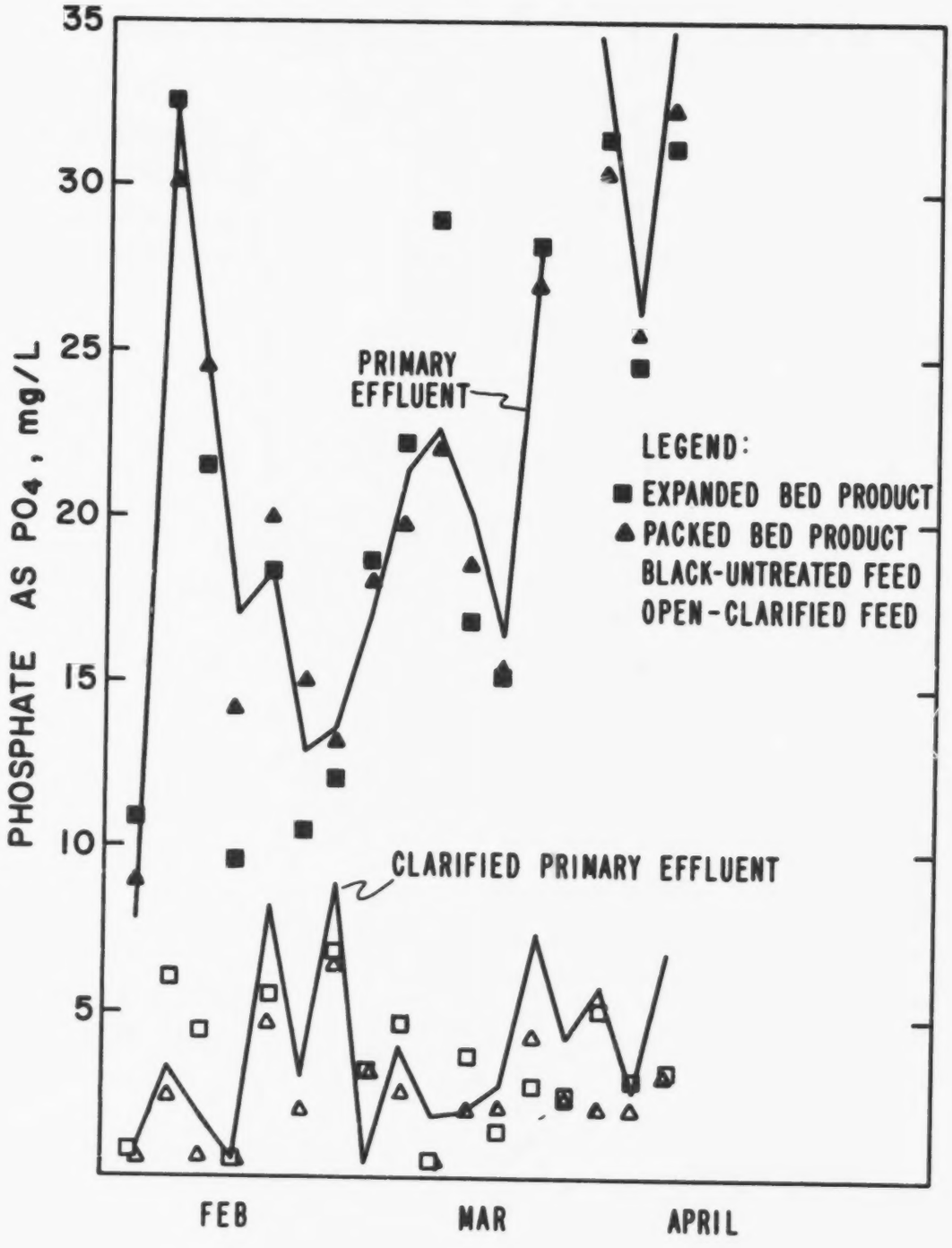

FIGURE 22 REMOVAL OF PHOSPHATE BY CHEMICAL CLARIFICATION AND 12-FT ACTIVATED CARBON

solids in the lower portions of the bed where there was relatively little bed expansion (see Figure 5).

The packed-bed systems required frequent cleaning to remove the accumulated solids. The first and second columns operating on primary effluent were cleaned 38 and 11 times; on clarified feed, the first and second columns were cleaned 31 and 4 times, respectively. During this same period of operation with primary effluent, the first expanded bed required cleaning twice, the second bed once. In these cases there appeared to be plugging in the bottom of the column only, which did not affect the operation of the expanded bed. With clarified feed, the expanded beds did not require any cleaning.

PHASE-TWO OPERATION: EXTENDED TREATMENT

Clarification

The coagulation-clarification system worked well during this operational phase, with only a few minor upsets caused by blockage of the primary effluent line to the pilot plant site. At no time during this phase of study was the alkalinity insufficient for proper coagulation with ferric chloride, which was used at an average rate of about 170 mg/l. The warmer wastewater (about 15°C) during the spring-summer period of operation was easier to clarify than the cold wastewater (5-10°C) of the Phase-One experiments.

Results of TOC analyses of the primary effluent and clarified primary effluent are given in Figures 23 and 24, along with the corresponding data for the effluents from the carbon columns. The weights of TOC and SOC involved in the clarification step are given in Table 4. During this period, about 64% of the TOC and 33% of the SOC was removed by chemical clarification. The concentrations of TOC and SOC were essentially equal for the clarified effluent, demonstrating the effective operation of the clarification system.

Adsorption

Because the TOC and SOC values for the clarified primary effluent feed were nearly equal, only the TOC results are plotted in Figures 23 and 24. The TOC data for the feed and the effluents from each column in the four-column, 24-ft deep carbon bed systems are also shown in Figure 23 for the expanded-bed adsorbers and in Figure 24 for the packed-bed adsorbers. For about the first 72 hours of operation (185 gallons throughput), the fresh carbon reduced the TOC of the effluent to 1-2 mg/l. For most of the remainder of the 125 days (about 450,000 gallons) of operation at constant flow, both carbon systems reduced the TOC to about 4 mg/l in the final product water. The weak primary effluent near the end of the run resulted from periods of heavy rain in the area. In Figure 25, the weights of TOC removed are plotted against weights applied for the 6-ft, 12-ft and 24-ft bed depths

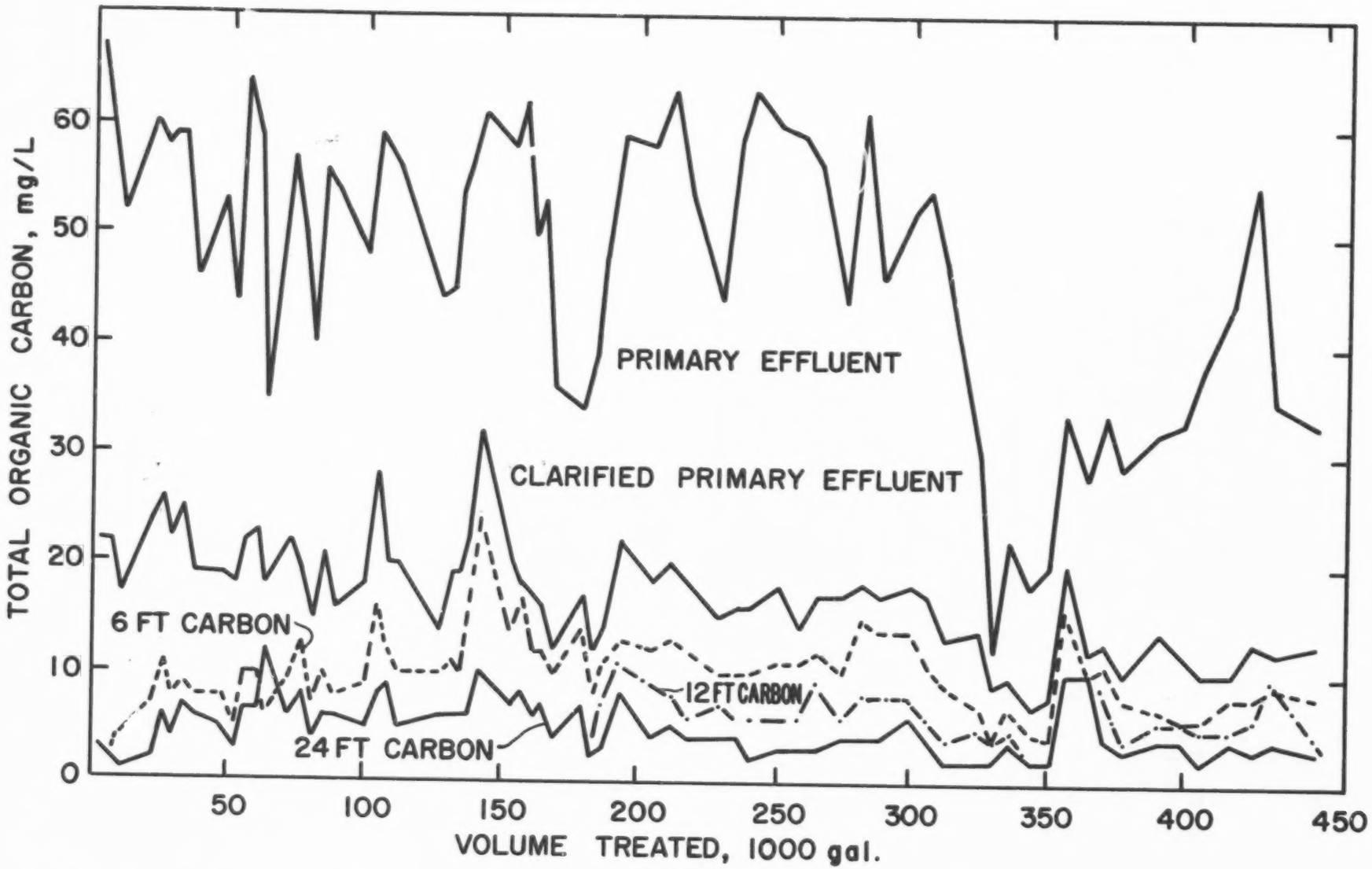

FIGURE 23 TREATMENT OF PRIMARY EFFLUENT BY CLARIFICATION AND ACTIVATED CARBON IN EXPANDED BEDS

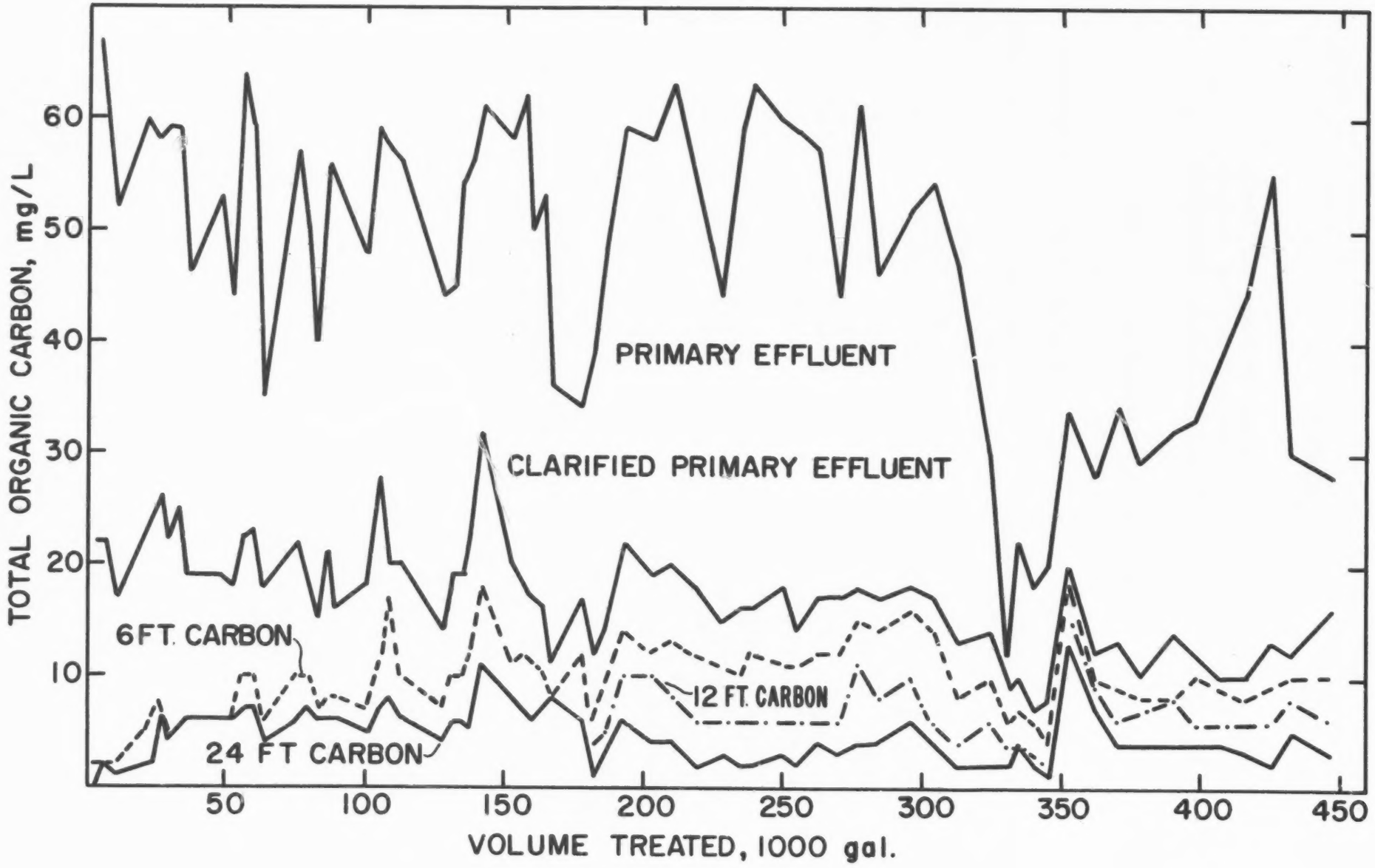

FIGURE 24 TREATMENT OF PRIMARY EFFLUENT BY CLARIFICATION AND ACTIVATED CARBON IN PACKED BEDS

TABLE 4

Removal of TOC and SOC From Primary Effluent by Chemical Clarification and Adsorption in 24-Ft Carbon Beds: Phase-Two Pilot Operation

Period - April 29 to September 2, 1969

	Packed Beds		Expanded Beds	
TOTAL VOLUME TREATED, gal.	447,464		449,680	
	Weight lb	Avg. Conc. mg/l	Weight lb	Avg. Conc. mg/l
Total Organic Carbon				
In Primary Effluent	172.5	46.3	173.0	46.3
In Column Feed	62.0	16.6	62.1	16.6
Removed	110.5		110.9	
Percent Removed by Clarifier	64.1%		64.1%	
Amount Removed in First Carbon Bed	25.4	6.8	25.1	6.7
Four Carbon Beds	46.7	12.6	45.9	12.3
Percent Removed by Carbon	75.3%		74.0%	
Average TOC of Product		4.0		4.3
Soluble Organic Carbon				
In Primary Effluent	79.0	21.1	80.6	21.4
In Column Feed	53.8	14.4	53.9	14.4
Removed	25.2		26.7	
Percent Removed by Clarifier	31.9%		33.1%	
Amount Removed in Four Carbon Beds	38.0	10.3	38.2	10.2
Percent Removed by Carbon	70.6%		70.8%	
Average SOC of Product		4.0		4.1
Loading on Activated Carbon				
TOC on First Bed lb/lb	0.30		0.30	
TOC on Four Beds	0.14		0.14	
SOC on Four Beds	0.11		0.11	

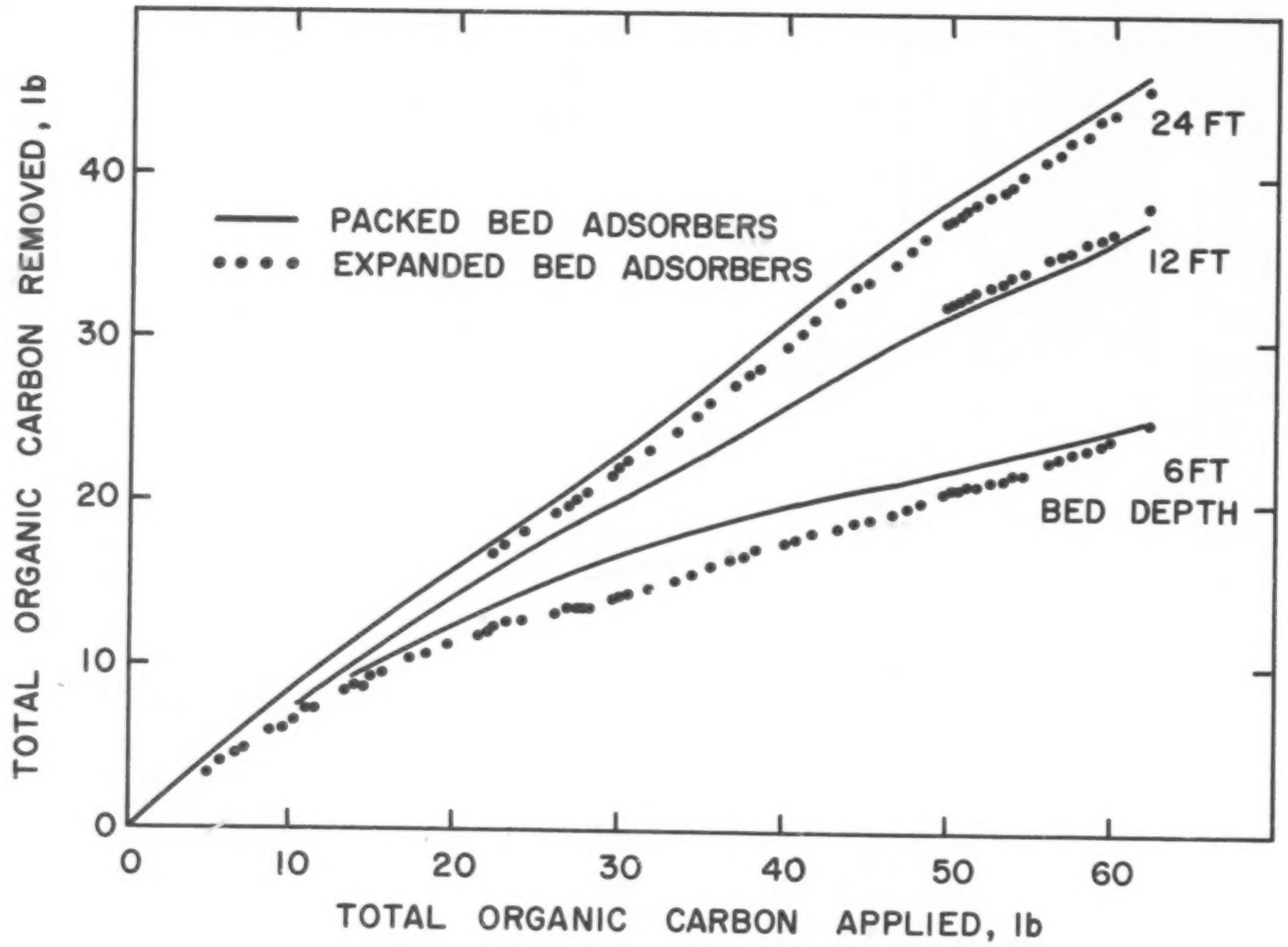

FIGURE 25 EFFECTIVENESS OF 24 FT OF ACTIVATED CARBON FOR REMOVAL OF ORGANIC CARBON FROM CLARIFIED EFFLUENT

in the two adsorption systems. A summary of TOC and SOC values for the entire run is presented in Table 4.

By the end of the Phase-Two experiment, the 85 pounds of activated carbon in the first 6-ft bed in both the expanded-bed and packed-bed systems had removed 25 pounds of TOC, thus the TOC loading on the activated carbon was about 30% by weight.

The removals of BOD in the clarification and adsorption systems during this experiment are shown in Figure 26. Chemical clarification removed about 2/3 of the BOD from the primary effluent, and the adsorption systems further reduced the BOD to an average of less than 5 mg/l in the final product water. In addition, there was an immediate oxygen demand of 1 or 2 mg/l in most of the samples for which the data were obtained.

Phosphate removal for this experiment is given in Figure 27. As expected, the ferric chloride reduced the phosphate content by about 90 percent from an average of about 30 mg/l to an average of about 3 mg/l. The activated carbon appeared to give a slight additional removal of phosphate, probably due to collection of floc particles and inorganic precipitates.

The removal of SS by clarification and adsorption was presented in Figure 11. The chemical-clarification generally reduced the SS content of the primary effluent to about 10 mg/l which includes a significant amount of inorganic solids. The same pattern is seen in the turbidity removal presented in Figure 28. The spike showing high turbidity and suspended solids in the clarified effluent in early June was caused by a failure of the coagulant feed pump before this sample was taken.

Both activated carbon systems accomplished further reduction in turbidity as shown in Figure 28, producing clear effluent with 1-2 JTU turbidity most of the time. The first packed bed was cleaned 48 times during Phase Two, and the other three beds 5, 2 and 1 times to remove the collected solids while the expanded beds required no cleaning at all.

The Phase-Two experiment was conducted during the spring and summer months, when the wastewater was warmer than during the Phase-One experiment. This warmer water permitted development of anaerobic conditions in both the expanded-bed and packed-bed carbon systems. The reducing conditions in the carbon beds were indicated by the presence of traces of H_2S in the carbon-treated water and by the formation of a slight haze in this water upon standing for some time. In some cases, the treated water contained sufficient ferrous iron to give a floc after exposure to air. On a few occasions, the iron content of the treated water was found to be as high as 5 mg/l as Fe^{++}, which on exposure to air would oxidize and precipitate.

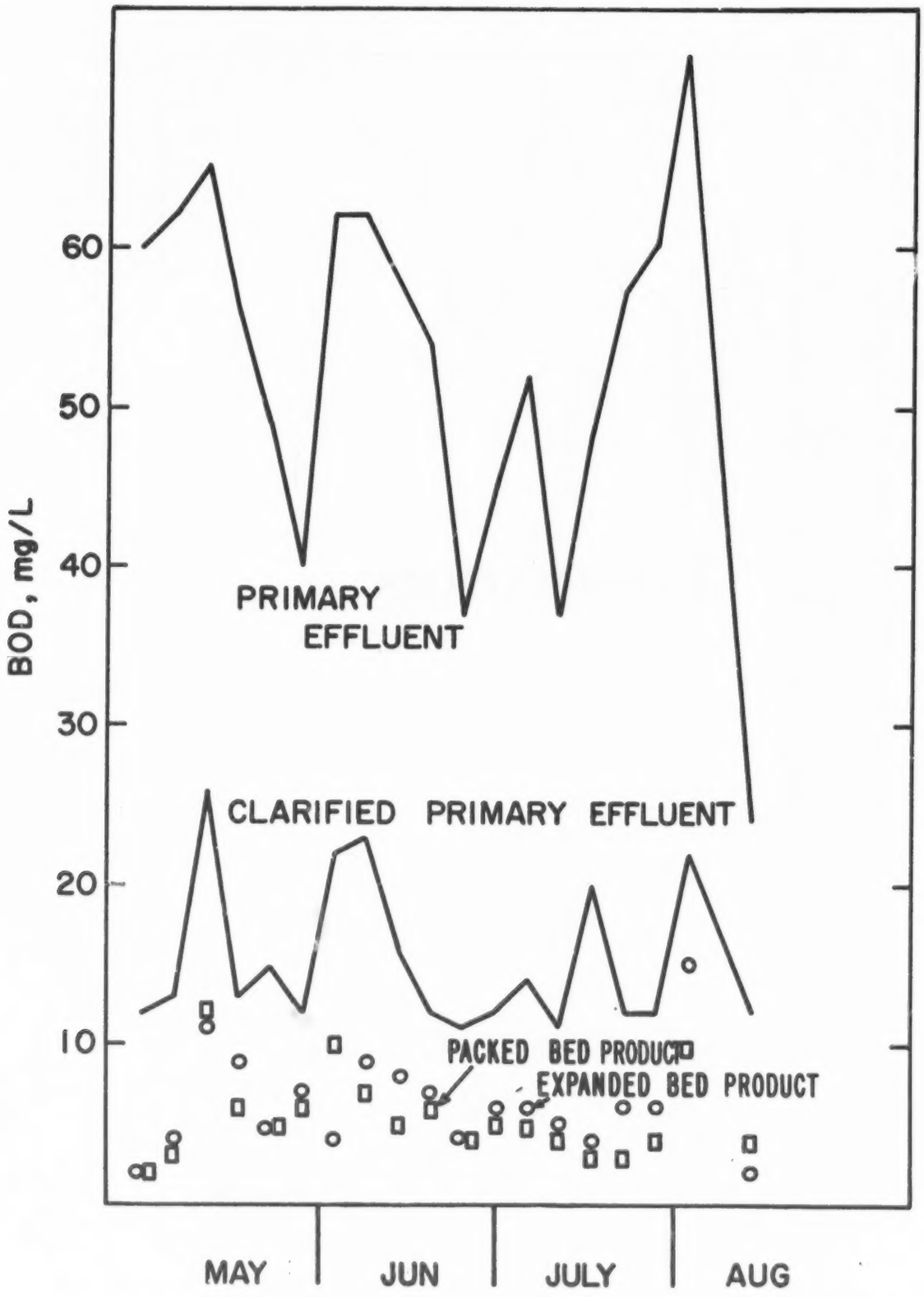

FIGURE 26 REMOVAL OF BOD FROM PRIMARY EFFLUENT BY CHEMICAL CLARIFICATION AND 24 FT ACTIVATED CARBON

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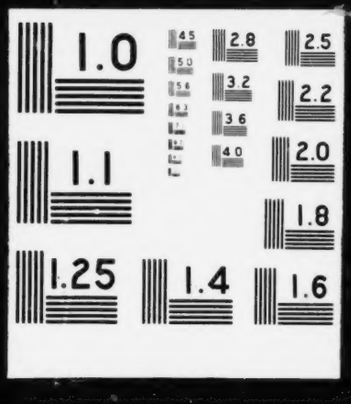

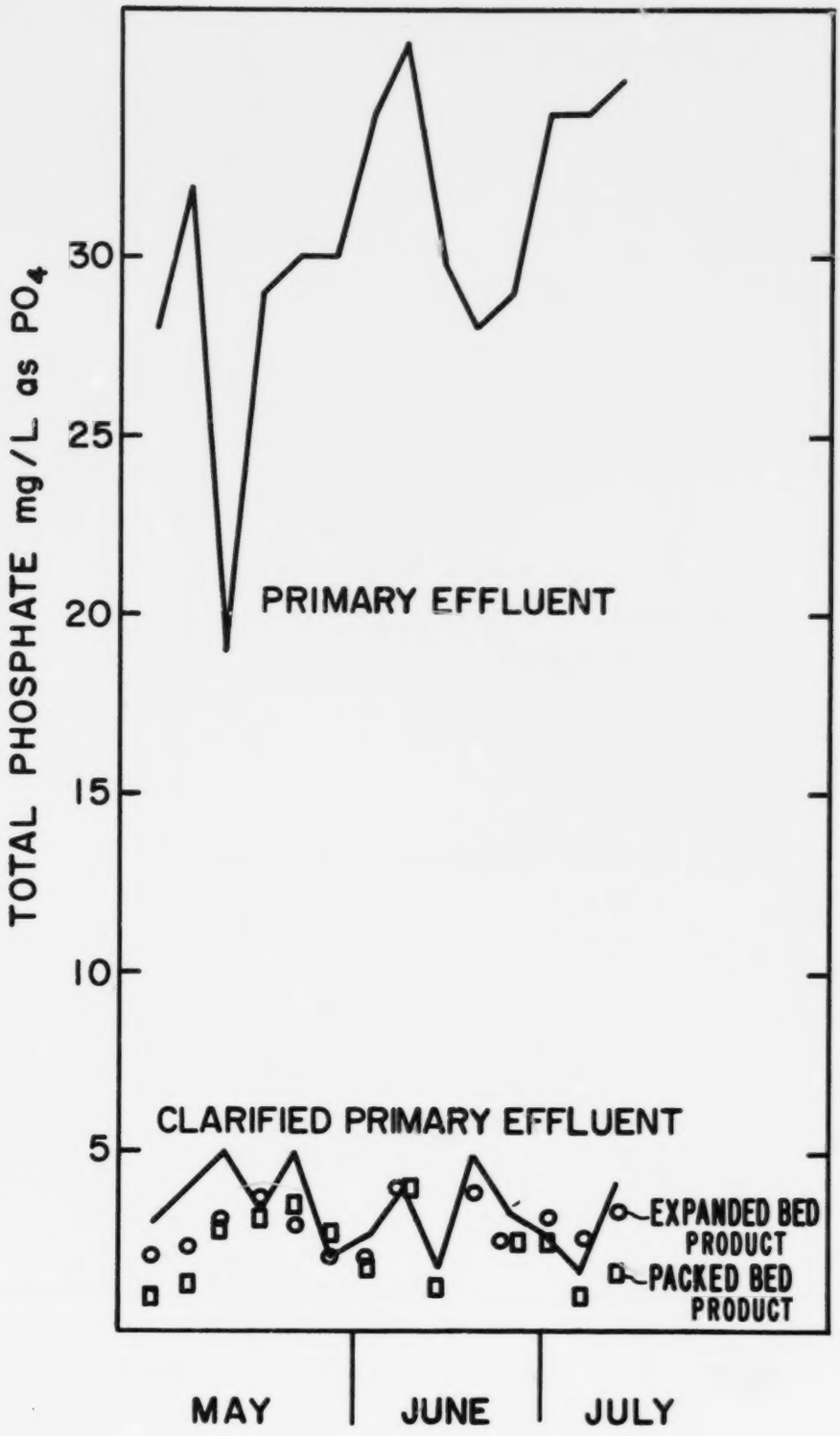

FIGURE 27 REMOVAL OF PHOSPHATE FROM PRIMARY EFFLUENT BY CHEMICAL CLARIFICATION AND 24 FT ACTIVATED CARBON

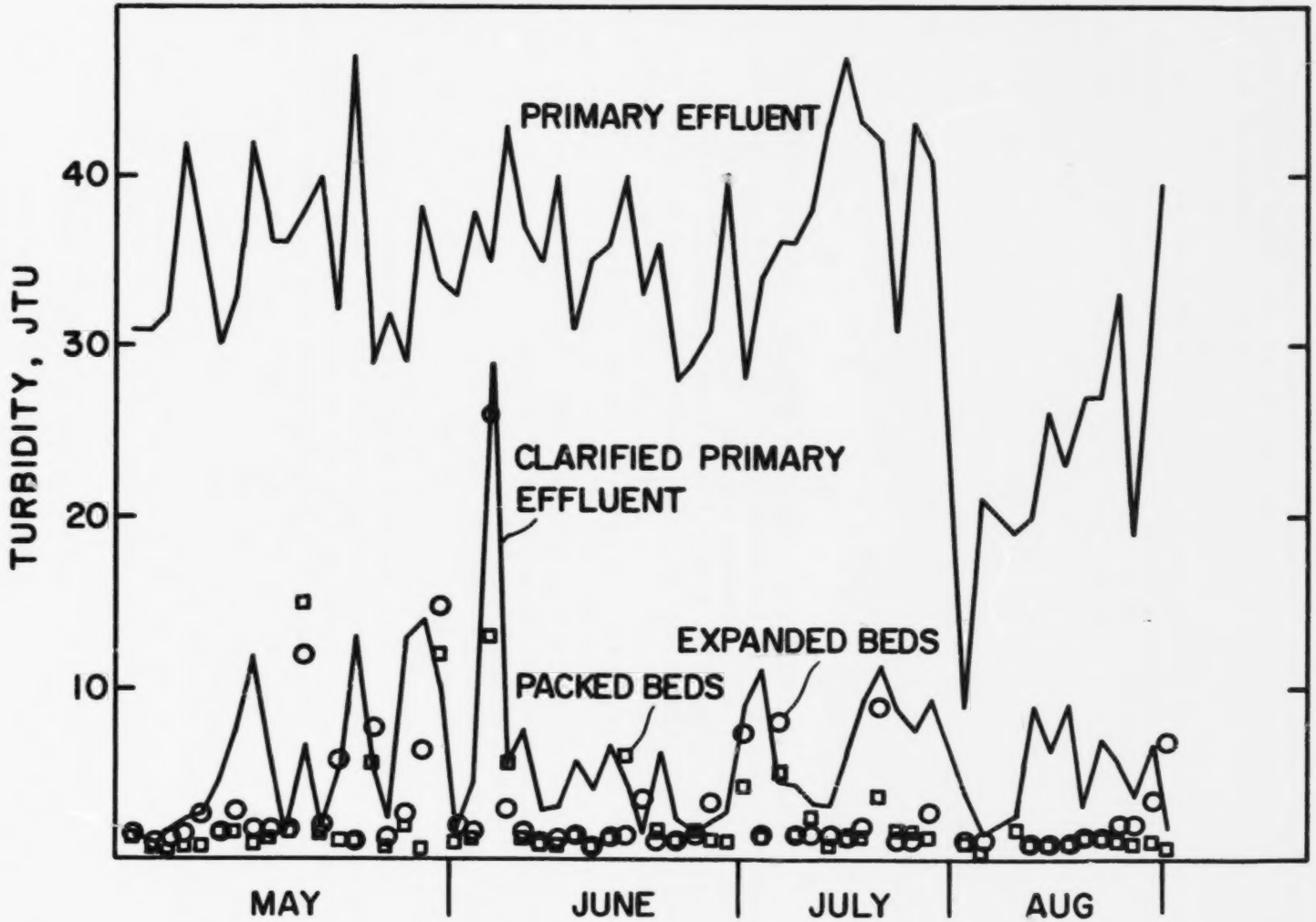

FIGURE 28 REMOVAL OF TURBIDITY FROM PRIMARY EFFLUENT BY CHEMICAL CLARIFICATION AND ACTIVATED CARBON BEDS

Several attempts were made to control the problems associated with the anaerobic conditions in the columns. Chlorine, as sodium hypochlorite, was added to the water from the clarifier and appeared to be moderately effective in reducing the H_2S odor in the clarified primary effluent. Aeration of the clarified effluent by bubbling air through the feed tank to the carbon columns reduced the H_2S odor, but also produced a biological floc in this tank, which tended to plug the packed column more rapidly. Neither of these solutions provided completely for control of the evolution of H_2S or the instability of the final treated water. Injection of oxygen from a cylinder of the compressed gas at a rate that would provide about 10 mg/l of O_2 in the influent to the columns, did reduce the evolution of H_2S but did not eliminate the instability of the treated water. Although the injected oxygen usually provided a dissolved oxygen (DO) concentration of 10 mg/l in the feed streams to the first carbon beds, the concentration of DO after the first bed in each system was 1 mg/l or less.

PHASE-THREE OPERATION: POSTCLARIFICATION

Adsorption

After termination of the Phase-Two experiment, the four-column systems containing partially spent carbon were again fed unclarified primary sewage, and the effluents from the beds were evaluated for post-clarification. During this 28 day period of operation no bed cleaning was required for the first 5 days. After that the first packed bed was cleaned 10 times and the other three required cleaning 4, 4 and 2 times, respectively. In spite of this almost daily cleaning, the total pressure in the packed bed system frequently went to 75 psig as compared to a maximum of approximately 40 psig during the Phase-One or Phase-Two experiments with clarified primary effluent. Results of analyses for TOC and SOC during this period are shown in Figures 29 and 30. Because of the down time required for cleaning the packed beds, and the slower rate of flow through the packed beds resulting from the higher pressure drop, the expanded-bed system which did not require cleaning treated about 15% more water over the same period. The removal of TOC by the expanded-bed system progressively declined until the total 24-ft was no more effective than the first 6-ft of the packed bed. The removal of SOC indicated a similar decline in the effectiveness of the expanded-bed adsorber under these conditions. The extensive solids removal by the filtering action of the packed bed, as indicated in Figure 31, probably contributed to most of this difference.

Post Clarification: Laboratory Studies

In jar tests conducted during Phase One and reported in Table 5, it was found that the coagulant dosages required for effective coagulation of primary effluent and primary

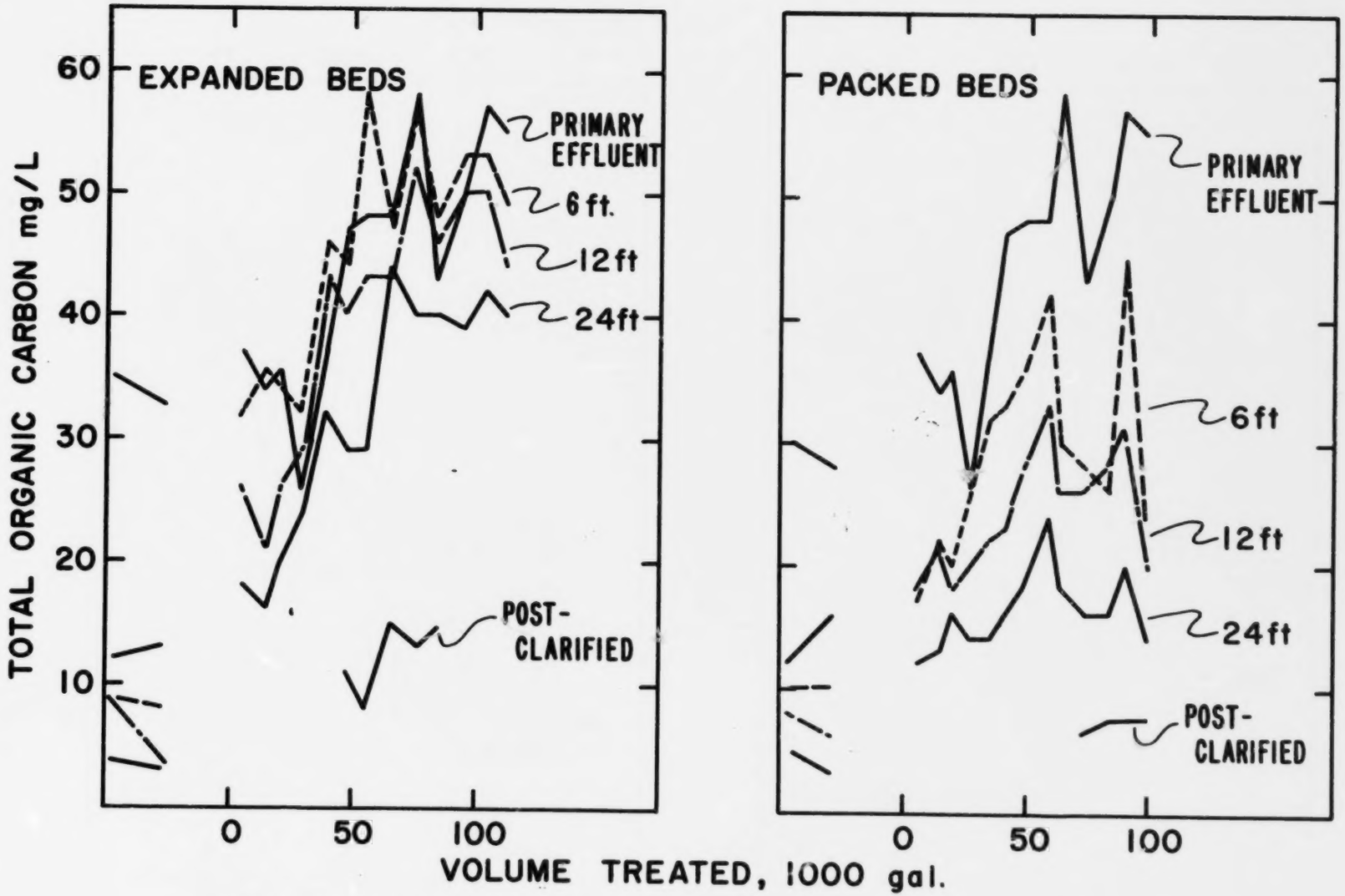

FIGURE 29 TREATMENT OF PRIMARY EFFLUENT IN ACTIVATED CARBON BEDS THAT HAD TREATED ~450,000 GALLONS OF CLARIFIED PRIMARY EFFLUENT - REMOVAL OF TOTAL ORGANIC CARBON

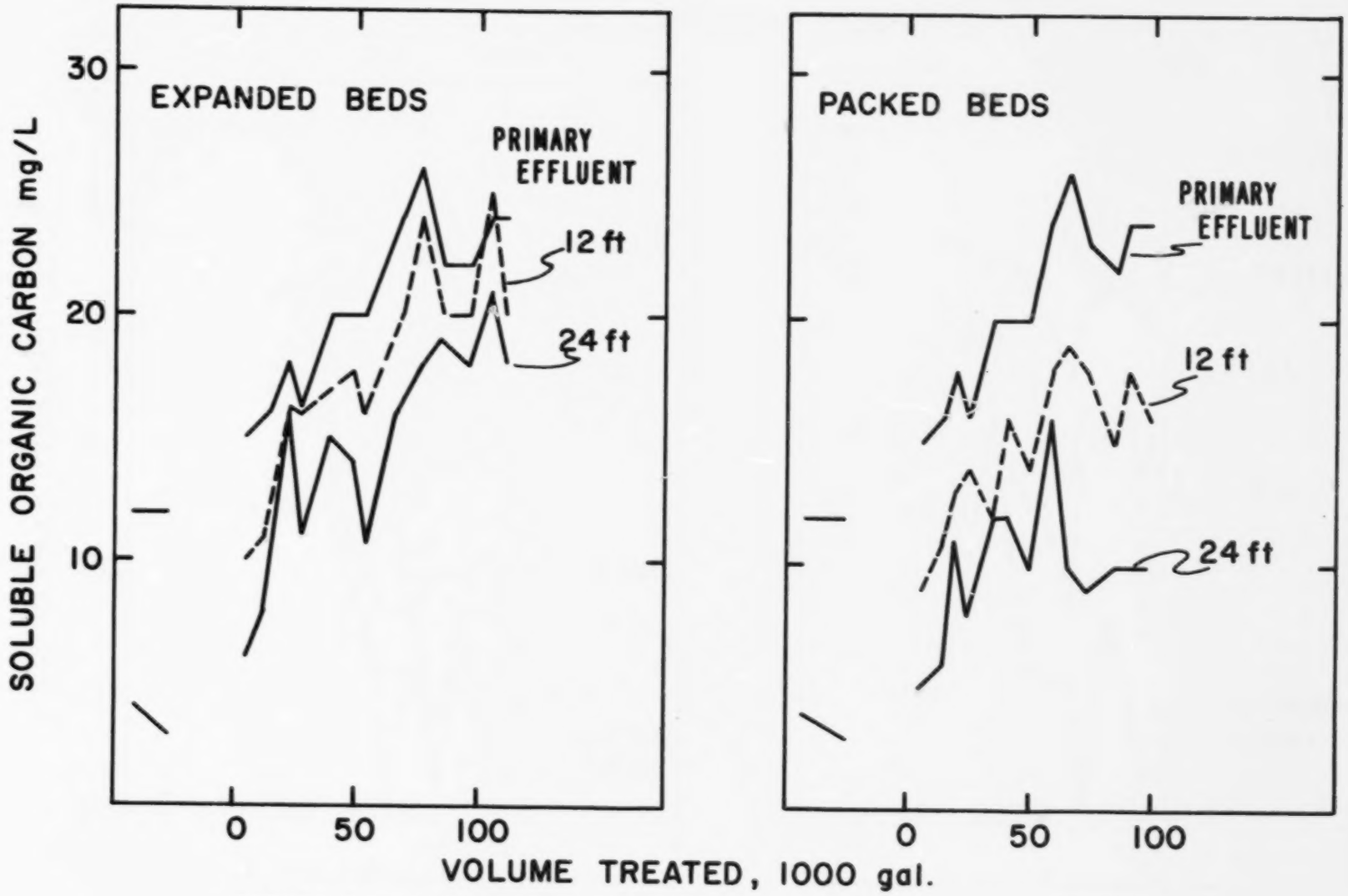

FIGURE 30 TREATMENT OF PRIMARY EFFLUENT IN ACTIVATED CARBON BEDS THAT HAD TREATED ∿450,000 GALLONS OF CLARIFIED PRIMARY EFFLUENT - REMOVAL OF SOLUBLE ORGANIC CARBON

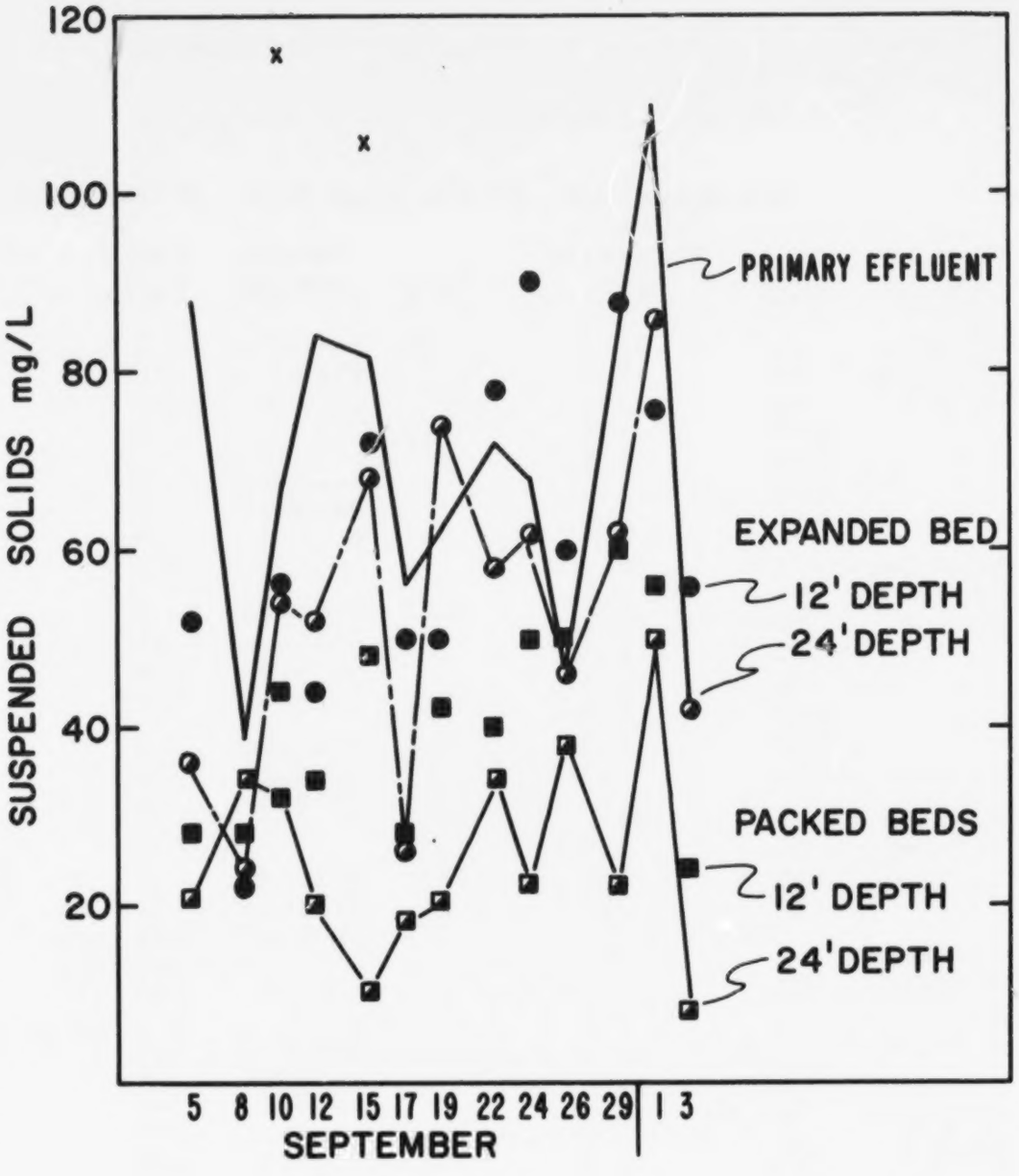

FIGURE 31 SUSPENDED SOLIDS IN TREATMENT OF PRIMARY EFFLUENT IN ACTIVATED CARBON BEDS THAT HAD TREATED 450,000 GALLONS OF CLARIFIED PRIMARY EFFLUENT

TABLE 5

Laboratory Comparison of Coagulant Requirements For Primary Effluent and for the Effluent From 12-Ft Expanded Beds of Activated Carbon

(Jar Tests: 2 Min Rapid Mix, 15 Min Slow Stir, 30 Min Settling)

Date	Sample and pH	$FeCl_3$ mg/l	Turbidity JTU
3/14	Primary Effluent pH 7.7	0	31
		77	9.3
		96	3.3
		115	1.5
		115	1.8
		134	3.0
		153	4.0
	Adsorber Product pH 8.1	0	28
		57	5.9
		77	5.4
		77	6.0
		96	3.3
		115	1.0
		115	3.2
		153	2.3
3/18	Primary Effluent	0	34
		95	5.5
		115	3.3
		134	2.1
	Adsorber Product pH 7.4	0	33
		95	4.2
		115	1.8
		134	1.9
3/19	Primary Effluent pH 7.5	0	29
		76	6.7
		115	2.1
		153	2.2
	Adsorber Product pH 7.7	0	28
		76	6.2
		115	4.5
		153	2.5
3/20	Primary Fffluent pH 7.6	0	27
		76	8.2
		115	2.9
		153	6.5
	Adsorber Product pH 7.8	0	23
		76	6.2
		115	2.3
		153	2.5
3/21	Primary Effluent pH 8.5	0	16
		38	5.8
		76	2.8
		115	1.7
	Adsorber Product pH 8.5	0	32
		38	8.8
		76	4.1
		115	2.6
4/3	Primary Effluent pH 8.6	0	32
		76	19
		115	2.3
		153	2.7
		170	3.5
	Adsorber Product pH 8.6	0	30
		76	13
		115	4.3
		153	2.7
		170	3.5
4/10	Primary Effluent pH 8.9	0	42
		96	16
		115	9.5
		134	6.9
	Adsorber Product pH 8.6	0	38
		96	9.4
		115	8.4
		134	3.2

effluent which had been passed through the activated carbon systems were essentially the same. Variations in dosages required for samples of either stream taken at different times were greater than variations in the dosages required for samples of the two different streams taken at the same time. For example, the amount of ferric chloride required to reduce turbidity to 2 to 3 JTU in the jar tests during this period varied from 75 to 150 mg/l as $FeCl_3$ for both the primary effluent and for the carbon adsorber product, whereas the dosages required for samples of the two different waters on any given day were nearly equal.

Results of jar tests of post-clarification following carbon treatment in 24-ft beds run during Phase Two are presented in Table 6. During this entire test the columns operated in an anaerobic condition, which clearly affected the coagulation results. It can be observed from Table 6 that there were times when coagulation of the adsorber product water with the ferric chloride was poor, the addition of the coagulant producing a black, finely divided solid. After aeration, either by allowing the sample to stand in air or by bubbling air into the sample, coagulation did take place.

Lime appeared to be a somewhat superior coagulant for post-clarification of the water produced from carbon treatment of primary effluent under anaerobic conditions. With lime there was no color in or dark appearance of the supernatant even when coagulating samples for which ferric chloride was ineffective.

In Phase One, as noted above, ferric chloride was found effective for coagulation of carbon-treated primary effluent. There were, however, no anaerobic conditions apparent in the columns during the Phase One tests. Lime was not evaluated at that time although it may be presumed that it also would have been effective.

Post-Clarification: Continuous Operation

The treated water from the expanded-bed and packed-bed systems was fed during separate periods to the pilot plant clarification system, which was therefore operating at one-half of the rate used for the previous operations. The TOC levels in the post-clarified carbon column effluents were shown in Figure 29. Suspended solids data are not presented. Clarification was inconsistent for the effluent from either column, and in order to permit coagulation it was necessary to operate the rapid mix propeller at a rate that would aerate the mixture. The clarified product never appeared to be as clear as clarified primary effluent, at times appearing yellow or dark. On occasions a scum of iron oxide formed on the surface of the clarifier.

TABLE 6

Laboratory Evaluation of the Post-Coagulation
of Effluent From 24-Ft Beds of Activated Carbon

(Jar Tests: 2 Min Rapid Mix, 15 Min Slow Stir, 30 Min Settling)

Date	Sample	Coagulant	Dose mg/l	Appearance Floc	Supernatant	Comments
9/11	ECU4	$FeCl_3$	40-95	Poor	Black	
	ECU4	$FeCl_3$	50	Fair	Haze	Tested after standing
			100	Fair	Slight Haze	for 2 hours in air.
	Primary (and Raw)	$FeCl_3$	50	Good	Slight Haze	
			100	Good	Clear	
9/16	ECU4	$FeCl_3$	150	Good	Clear	Aeration Increases
			180	Good	Very Clear	pH from 7.9 to 8.6
	Primary (and Raw)	$FeCl_3$	60	Fair	Haze	
			72	Good	Clear	
9/17	ECU4	$FeCl_3$	50	Fair	Haze	
			75	Fair	Slight Haze	
			100	Good	Clear	
			120	Good	Very Clear	
		Lime	75	Fair	Haze	
			125	Good	Slight Haze	
	PCU4	$FeCl_3$	50	Poor	Black	
			75	Poor	Black-Grey	
		Lime	75	Fair	Haze	pH 9.4
			125	Good	Slight Haze	pH 9.8
9/19	ECU4	$FeCl_3$	72	Fair	Haze	
			108	Good	Slight Haze	
			144	Good	Very Clear	
		Lime	100	Good	Slight Haze	pH 9.4
			150	Good	Very Clear	pH 9.8
9/23	Primary	$FeCl_3$	108	Good	Slight Haze	
			144	Good	Very Clear	
		Lime	125	Good	Slight Haze	pH 9.6
			175	Good	Very Clear	pH 10.0
	ECU4	$FeCl_3$	108	Fair	Haze Dark	
			144	Good	Haze Dark	
		Lime	125	Good	Slight Haze	pH 9.4
			175	Good	Clear	pH 9.8

ANALYSIS OF SPENT CARBONS

At the conclusion of the continuous treatment experiments, the partially spent carbons were removed from each column, weighed, and subjected to several analyses. The results of these analyses are given in Table 7. In addition, the weight of SOC removed by each column is reproduced in this table to facilitate comparison with the apparent increase in weight of the activated carbon.

The total weight of the dry spent carbon from each column was calculated from the total weight of the drained carbon and the moisture content as determined by drying samples of the carbon at 140°C to constant weight. Likewise, amounts of volatile matter (at 900°C) were determined on samples of the carbons, and the total devolatilized weights calculated from these values. In general, the carbon in the first bed in each series contained more volatile matter, and showed a greater increase in weight.

Iodine and methylene blue adsorption tests were run on the fresh activated carbon and on samples of the dried and devolatilized spent carbons. These measurements indicated that a considerable portion of the original adsorptive capacity of the carbon was recovered by treatment at 900°C for two hours in the absence of air. All of the carbons showed an increase in ash content, some of which may have been due to iron from the coagulation operation.

CARBON PARTICLE SIZE EFFECTS

At the low flow rate of 1 gpm/ft^2 used for these particle size studies, no expansion or particle motion was observed in the bed of 8 x 16 adsorbent. Therefore, this column was subject to the usual problems of a fixed bed. There were instances in which solids accumulation resulted in the entire bed being lifted as one mass of carbon by the upflowing wastewater. It was necessary to clean this bed frequently to break up the plugs of carbon.

Data on the removal of TOC for the two columns are presented in Figure 32. Initially, removal of TOC for the two columns was similar but the TOC removal by the bed of 8 x 16 particles declined to about 2/3 of the TOC removal by the 50 x 100 particles by the end of the run.

POLISHING COLUMN

During the course of the Phase-Two operation, use of a fresh activated carbon post-treatment was evaluated for periods up to 48 hours. The results of these experiments, presented in Table 8, show effective reduction of the TOC which remained after the treatment provided by the 24-ft of activated

TABLE 7

Analyses of Spent Carbons From The Pilot Operations

Column	Drained Wt., lbs	Dry Wt., lbs	Devolatilized Wt., lbs	SOC Removed, lbs	Moisture, Wt. %	Volatile Matter, Dry Basis, Wt. %	Ash, Dry Basis, Wt. %	Iodine Number, mg/g Dried	Iodine Number, mg/g Devolatilized	Methylene Blue Adsorption mg/g Dried	Methylene Blue Adsorption mg/g Devolatilized
Phase I Tests											
PCU1	207.2	120	102.8	30.7	42	14.4	7.15	610	865	230	375
PCU2	182.1	108	92.9		40.6	14.0	7.3	625	880	230	360
ECU1	195.9	112	95.5	31.3	42.7	15.0	7.4	630	900	230	395
ECU2	188.1	108	92.4		42.8	14.2	7.5	610	880	230	360
PCC1	186.9	108	92.6	25.6	42.2	14.2	5.9	600	900	200	355
PCC2	183.7	102	90.0		44.7	11.5	5.9	700	910	220	380
ECC1	204.6	115	99.0	24.0	43.6	14.1	5.8	590	870	200	360
ECC2	180.0	104	91.5		42.4	11.8	5.8	700	940	240	345
Original		85				1.1	5.3	940		465	
Phase II Tests											
PCC1	182.0	107	90.9	25.4	38.3	19.0	6.1	390	760		
PCC2	174.9	106.4	91.0	12.0	41.3	14.4	7.5	510	790		
PCC3	179.1	101.9	89.7	6.5	43.8	11.7	7.8	640	860		
PCC4	186.1	93.8	86.7	2.9	50.2	7.6	7.4	800	940		
ECC1	188.8	99.8	83.5	25.1	47.1	16.3	7.0	415	775		
ECC2	185.4	105.0	90.4	15.3	43.3	13.9	7.3	500	790		
ECC3	185.4	100.9	89.5	5.0	45.6	11.2	7.4	620	870		
ECC4	183.2	89.2	83.6	2.4	51.3	7.3	7.0	730	910		
Original		85			0.5	1.0	5.7	1120		520	

All columns originally charged with 85 lbs of activated carbon.

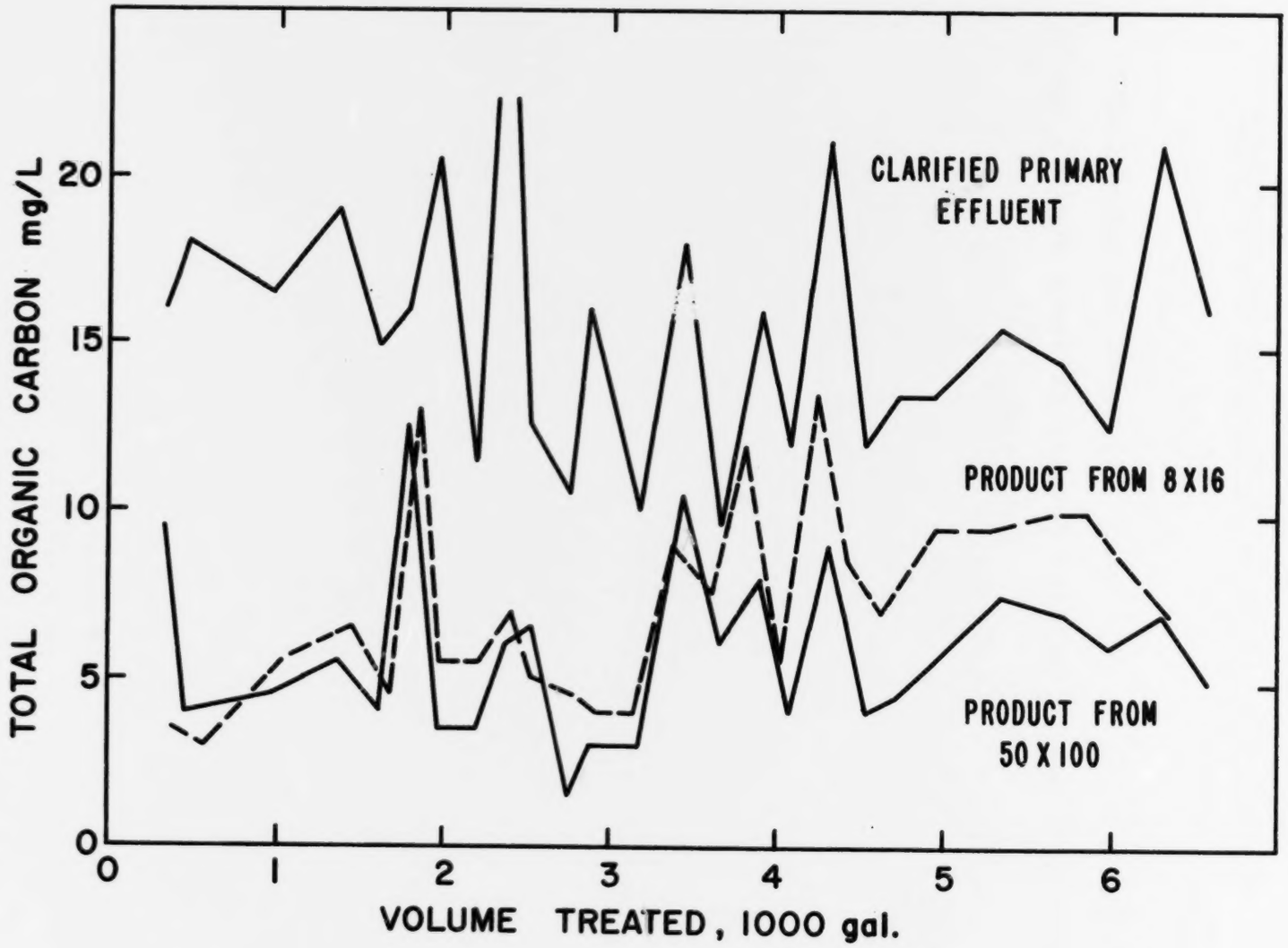

FIGURE 32 TREATMENT OF CLARIFIED PRIMARY EFFLUENT FLOWING UPWARD THROUGH 4-FT DEEP BEDS OF ACTIVATED CARBON WITH DIFFERENT PARTICLE SIZES AT 1 gpm/ft^2

TABLE 8

Evaluation of Fresh-Carbon Polishing of
Product Water From 24-Ft Expanded-Bed Adsorbers

Column: 1-in.^{2} ∿1' Deep 92 Grams Activated Carbon

Carbon Treated Clarified Primary Effluent Feed ∿5 gpm/ft

Date	Time Hours	TOC In	TOC Out
7/22	2	5.5	1.5
	4	4.8	2.0
	6	3.8	1.5
	8	4.5	3.5
	23	5.0	4.0
7/25	1	3.5	<0.5
	2	2.8	0.5
	8	2.0	<0.5
7/29	1	1.5	<0.5
	2-1/2	1.0	<0.5
	5	1.0	<0.5
	7	1.5	<0.5
8/27	1	4.0	<1.0
	2	3.5	1.5
	3	4.0	<1.0
	7	3.2	1.5
	12	3.5	1.5
	24	5.0	2.5
	48	5.0	4.0

carbon to a level of 1 to 2.5 mg/l for a period of 24 hours. The 24-ft carbon beds were anaerobic during this operation, and at times produced unstable product water which became cloudy. However, the product from the short polishing bed was stable even after the carbon bed had been on stream for 48 hours.

DISCUSSION AND CONCLUSIONS

CLARIFICATION

Chemical clarification with ferric chloride as used in this study proved very effective for consistent removal of suspended and colloidal matter from a primary effluent.

During the extended Phase-Two test program (125 days) the clarification system consistently produced a reasonably clear effluent and, at the same time, removed TOC. It was expected that removal of suspended solids would result in TOC reduction, but the removal of TOC was somewhat higher than anticipated. The extent of removal of TOC by coagulation may be related to the nature of the solid matter in the particular wastewater studied.

A somewhat surprising result was the accompanying average removal of 32-33% of the SOC by the chemical clarification step. This SOC removal may be a matter of definition, in that SOC was defined as the organic carbon measured in the filtrate passing a 0.45-micron membrane filter. Thus, the removal of SOC by clarification indicated that a significant portion of this organic matter may have been present in the form of colloidal or particulate matter smaller than 0.45 microns or was reduced by biological activity. Removal of this fraction may have been especially beneficial to the subsequent treatment by activated carbon, since colloidal particulate matter is not adsorbed nor otherwise readily removed by activated carbon in either an expanded or packed bed.

The TOC and SOC removal was accompanied by a significant reduction in the BOD. The average BOD of the primary effluent averaged about 50 mg/l since the ELSA plant primary settler removed about 50 percent of the raw sewage BOD. The chemical coagulation and clarification removed another 70 percent resulting in a clarified primary effluent with an average BOD less than that expected in secondary effluent from the trickling filter treatment.

As expected, the coagulation system accomplished very effective removal of phosphorous in addition to providing a high degree of clarification and removal of organic matter. It is presumed that the phosphate was removed by precipitation of a ferric phosphate. The phosphate therefore consumed a part of the ferric chloride. Thus, ferric chloride dosage requirements can be expected to vary with variations in the phosphate content of the sewage.

Since phosphate removal from waste effluents is a matter of considerable interest, this factor adds another advantage to the chemical pretreatment, which, while accomplishing clarification for more effective removal of organic matter by activated carbon, also provides a high percentage of phosphate reduction.

ACTIVATED CARBON TREATMENT

Removal of Organic Matter

The principal study directed toward meeting the objectives of this project was the extended test run of Phase Two which was a direct comparison of the effectiveness of the expanded-bed and packed-bed modes of carbon adsorption for treating primary effluent. Sufficient stages of carbon beds were used to accomplish essentially complete organic removal. In preparation for the extended run, the effects of pretreatment of the primary effluent were evaluated in Phase One using shorter activated carbon beds which were not expected to accomplish as much organic removal. On the basis of analyzing the possible pretreatments and running initial laboratory studies, the Phase One pilot plant runs were limited to a comparison of the effects of a high degree of clarification using chemical coagulation against no pretreatment.

The results indicated that the use of chemical coagulation and clarification was quite desirable. When the suspended solids in the primary effluent were removed, nearly all of the organic matter remaining was that defined as SOC, which could be effectively treated by the granular activated carbon. The result was a relatively low organic content in the effluent from the two column (12-ft carbon bed) systems. Therefore, in the extended pilot plant test run of Phase Two using two four-column (24-ft carbon bed) systems, the primary effluent was highly clarified prior to feeding to the adsorbers.

In the Phase One studies the expanded-bed mode of contacting was somewhat inferior to the packed-bed mode, particularly, as would be expected, for removal of TOC from untreated primary effluent. With the clarified effluent feed, the difference between the two modes of carbon contacting was less but still existed, probably due to suspended solids that remained in the primary effluent when the coagulation-clarification system operated poorly as noted in the earlier discussion. In the Phase Two runs, the performance of the expanded-bed and packed-bed adsorbers was essentially equal for organic carbon removal. In Phase Two, the clarification was more consistently effective and TOC essentially was all SOC. Thus, the effect of organic matter present in the effluent as solids was eliminated. During this test, after the clarification had removed substantial quantities of TOC and SOC from the primary effluent, both adsorption systems reduced the organic content to an average of about 4 mg/l, which appeared to be a lower limit. This was an average removal of 75% of the TOC and 70% of the SOC. Both adsorber systems continued producing this low organic content effluent essentially throughout the 125 days of test and it appeared that they could have continued this effectiveness for an additional time. However, the test was stopped to allow time to investigate post-clarification during the Phase Three period.

The conclusion that the carbon adsorption effectiveness could have continued beyond the 125 day test period is supported not only by noting that the organic content of the final effluent was not yet increasing, but also by considering the behavior of the first column in each series compared to that of the other three columns. Both of the first columns removed on the average more than half (55%) of the organic matter removed by the total system. This resulted in the first beds being loaded to about 30% by weight with TOC while the average TOC loading for the entire system of four beds was 13.5%. Despite the 30% loading, the first beds were still removing about 25% of the TOC from the clarified feed at the termination of the tests. If TOC represents 50% by weight of the organic matter, then the loading on the carbon in the first bed was actually 60% by weight which is substantially greater than the usual adsorption capacity of carbon. This high loading may have been due to solids collection on the carbon. However, it is also believed that biological activity in the bed actually accounted for some of the apparent organic removal ascribed to the carbon. This affect of biological activity is discussed further later in this Section.

BOD removal in the clarification-adsorption system roughly paralleled the TOC removal. The activated carbon adsorption systems further reduced the BOD to 4-5 mg/l, as may be noted in Figure 24. These results indicate that the BOD was largely present in the particulate and colloidal matter and not as soluble organic (SOC). The BOD of the product, representing only 4-5% of the raw sewage BOD - or 95 to 96% removal - was considered to be acceptable and no efforts were made to find ways to achieve further reduction.

Thus, the treatment of sewage by clarification and adsorption achieved high removal of both organic carbon and BOD, as contrasted with primary-secondary treatment plants which are reported to be capable of removing 90% of the BOD but less (80%) of the total organics.[4] Adsorption can remove the organics that are considered refractory to biological processing, and at the same time remove most of the biodegradable organics in the wastewater.

Based on the organic removal results during the test period and ignoring any additional removal capability of the system, it is possible to estimate a carbon dosage for this method of treatment using either the expanded-bed or packed-bed mode of adsorption. It is assumed that an adsorption system would consist of at least two stages and that operation would be countercurrent. When the carbon in the first phase became saturated, it would be removed from the system for regeneration and the second stage would then become the first stage.

In this test program, if it is considered that the first beds of 85 pounds of carbon each were spent after treating 450,000 gallons each (4500 bed volumes for each four-column system) this would represent a dosage of 189 pounds of carbon per million gallons of effluent treated. To estimate system dosages from this loading for the first beds, several factors must be taken into account: (1) the carbon might have been exhausted earlier if the sewage had maintained its strength rather than being reduced in organic content by heavy rain during part of the 125 day run; (2) the second beds in the system had removed half as much TOC as the first bed, Figure 25 and Table 4, and if these beds were moved to the first position with half of their capacities exhausted, they would only be able to treat half the effluent, thus doubling the carbon requirements; (3) the carbon after regeneration would be expected to have a lower capacity than fresh carbon. On these bases, a conservative estimate of the activated carbon requirements for such continuous processing would be about 500 pounds per million gallons of water.

The Phase Three experiments which demonstrated that post-clarification was not a desirable approach for either expanded-bed or packed-bed modes of adsorption, also demonstrated the adverse effects that large amounts of suspended solids may have on carbon adsorption systems after the carbon has been in use for some time. In this test period, the filtering action of the packed beds was very apparent in that they definitely showed greater capacity than the expanded beds to remove TOC and BOD, and to some extent, SOC. Using the carbon that had previously been used in the Phase Two experiments, the TOC removal data initially indicated that the expanded beds were slightly inferior to the packed beds. As the run progressed, however, the TOC removal effectiveness of the expanded beds drastically declined. During this time, the first packed bed (6-ft) removed as much TOC as the entire 24-ft expanded-bed system and the first two packed beds (12-ft) removed as much SOC as the 24-ft expanded bed.

However, during the course of this operation, it was necessary, because of excessive pressure drop, to clean the packed bed daily to remove the accumulated suspended solids. This frequent cleaning of the first packed bed was apparently beneficial to the performance of the subsequent packed beds in the series. Because the pressure drop remained low, the expanded beds were not cleaned during this period and the suspended solids content of the product water frequently exceeded that of the feed.

This test series definitely confirmed the conclusion from the Phase One studies that removal of suspended solids before adsorption is beneficial to the efficient operation of

activated carbon systems. In the case of the packed bed, a thoroughly clarified feed permitted operation at lower pressure and less frequent backwashing. For expanded-bed systems, clarified feed is also desirable for efficient operation by preventing excess solids accumulation with a resulting decrease in the adsorptive efficiency of the activated carbon.

Biological Activity in the Carbon Beds

The high organic loadings observed in the first beds in the activated carbon adsorber systems and the continued organic removal under these conditions indicated that another mechanism was involved in addition to that of adsorption. Activated carbon does provide an excellent surface for concentration of organic biological substrate materials which appeared to provide a beneficial biological growth. This biological activity did not appear to hinder the adsorption process in any observable fashion.

During the course of the Phase Two extended run, the biological activity on the activated carbon beds generally produced anaerobic conditions as evidenced by evolution of H_2S. Without aeration or other approaches to control the anaerobic environment, this biological activity had the disadvantage of creating an immediate dissolved oxygen demand (IDOD). This IDOD was probably due to the H_2S and the presence of iron carried over as Fe(III) from the coagulation stage and then reduced to Fe(II) as a result of the anaerobic conditions in the carbon adsorption systems.

Control of the anaerobic conditions and the resulting objectionable H_2S formation was not completely solved by the application of either hypochlorite, air or oxygen prior to the first carbon beds only. Even with a concentration of 10 mg/l DO in the feed to the first bed there was no DO remaining in the feed to the next three beds in series. This apparently controlled the conditions in the first bed, but not in the later beds.

It appears that control of the anaerobic conditions will require having a positive DO in the feed to each column. With expanded-bed adsorbers, this can be accomplished by using open vessels and overflow troughs designed to provide aeration.

Operational Advantage of Expanded-Bed Contactors

Although there were no significant differences in the organic removal characteristics of the expanded-bed and packed-bed adsorbers with highly clarified feed, there were, as observed previously in pilot studies on the treatment of secondary sewage effluents[1], some significant operational differences. None of the four expanded-bed adsorbers required any cleaning or maintenance over the four-month period of operation with the clarified primary effluent feed; flow rates

remained constant without appreciable increases in head loss through the four columns in series. Conversely, even with the highly clarified primary effluent, the head loss in the packed-bed adsorbers increased steadily, requiring increased pumping pressures and frequent cleaning and backwashing.

POLISHING TREATMENT CONCEPT

At the start of the Phase Two experiment the first 6 ft of activated carbon initially removed essentially all of the TOC. After about 72 hours, the effectiveness of the first bed had changed somewhat to give an effluent containing about 6 mg/l. This level then very slowly increased to about 12 mg/l during the next 1800 hours while the three additional columns in the system reduced the TOC to a level of 2 to 6 mg/l. These results indicated that the carbon may have rapidly become saturated with some fraction of the organic matter and that this effect prevented complete organic removal from then on. Therefore, it was proposed that the use of a final polishing bed of fresh activated carbon might permit a closer approach to achieving continuously organic-free, renovated water. In the preliminary experiments reported, small columns containing a 1-ft bed depth of fresh activated carbon were found to be effective for removal of most of the remaining TOC over a period of about 24 hours. If further tests confirm that this polishing action can be depended upon with regenerated carbon, development of a very low cost regeneration or a means of achieving high loading to make the concept economically feasible would appear justified.

The organics adsorbed in the short bed following carbon treatment are evidently only weakly adsorbed and at a slow rate, and thus could possibly be removed readily in a rapid, simple reactivation system. This approach should be investigated further in an effort to devise a treatment scheme for complete organic removal in applications where the specifications for reused water are especially demanding. The main carbon beds would be used to adsorb the major part of the contaminants with the final polishing bed used to complete the organic removal and to provide the higher quality product water.

CARBON PARTICLE SIZE EFFECTS

It was proposed by Morris and Weber[13], that the expanded-bed mode of operation would allow for the use of smaller particles of granular activated carbon, with a greater capacity and a higher rate of adsorption of organics from solution. The present experiment on the effects of particle size was conducted to determine on a reasonable scale if it would be practical to use smaller particle carbon in an expanded-bed adsorber and if indeed advantages would accrue. Two widely different-sized fractions of an experimental carbon were used. Based on diameters, the 8 x 16 fraction had an average particle size seven times larger than the average particle size of the 50 x 100 fraction

(1.4 vs. 0.2 mm). Thus, the bed of smaller particles presented about seven times as much external surface to the water. Although the two size fractions were taken from the same batch of activated carbon, it was found that there was a significant difference in the adsorptive capacity of the two as measured by both iodine and methylene blue adsorption.

The system containing the smaller particles was more effective for removal of TOC from clarified primary effluent for the entire test, with a greater difference developing as the run progressed, suggesting a larger adsorptive capacity as well as a higher rate of adsorption for these smaller particles.

While there may have been other factors operating, the 50 x 100 particles provided greater organic removal. However, while there were no operating problems with the smaller particles at this flow rate and complete expansion of the bed was attained, a practical application would probably require higher specific flow rates to minimize the size of the adsorption vessels. Some particle size range intermediate between the two chosen for these tests may be optimum to provide a balance between capacity of the adsorbent and vessel size.

PROPOSED TREATMENT SCHEME

On the basis of the results obtained in the extended test in Phase Two of this study, a complete physicochemical wastewater treatment system is proposed. The concept proposed consists of clarification of raw sewage followed by adsorption of the soluble organics remaining in the clarified effluent on activated carbon. Pilot-scale experiments were conducted with primary effluent to avoid problems due to large or fibrous solids, and by using ferric chloride for convenient metering of the coagulant solution. The proposed scheme is based on coagulating raw sewage with lime.

To obtain data for design and analysis purposes, laboratory jar tests were conducted on raw sewage, primary effluent and secondary effluent taken at the same time. Coagulation with ferric chloride at 120 mg/l or lime at 250 mg/l produced very clear supernatant in all cases. Results of clarification and subsequent contacting of the supernatant are given in Table 9. While the initial TOC values are low, there appears to be little difference in the effectiveness of the coagulants for removing organic carbon, or on the subsequent adsorption. Gross solids present in the raw sewage settled rapidly under the conditions in the jar test, and did not appear to affect the coagulation.

Similar experiments were conducted to determine the effect of pH on organic removal by adsorption on granular activated carbon after clarification with lime or ferric chloride. Results of these tests in Table 10 show insignificant effect due to coagulation or adsorption at the higher pH.

The use of lime as a coagulant provides good clarification, a rapid settling sludge, and in addition, permits the use of a

TABLE 9

Laboratory Studies of Coagulation With Ferric Chloride and Lime and The Effects on Subsequent Carbon Adsorption

Date	Waste Stream	pH	TOC mg/l	Coagulation Reagent[1]	pH	TOC mg/l	TOC After Carbon Contacting[2] of The Supernatant 700 mg/l	2000 mg/l
8/19	Raw Sewage[3]	7.7	30.5	$FeCl_3$	6.3	13.0	7.5	6.5
				Lime	10.8	16.0	10.0	5.0
	Primary Effluent	7.3	29	$FeCl_3$	6.0	13.0	5.0	5.5
				Lime	10.7	12.5	4.5	4.5
	Secondary Effluent	7.3	18	$FeCl_3$	6.0	5	3.5	2.5
				Lime	10.7	6	2.5	4.0
8/26	Raw Sewage	7.9	50	$FeCl_3$	6.3	19.0	5.0	3.0
				Lime	10.6	21.5	7.5	6.0
	Primary Effluent	8.5	31	$FeCl_3$	6.5	12.0	5.0	3.0
				Lime	10.8	11.0	6.0	4.0
	Secondary Effluent	7.0	9.5	$FeCl_3$	6.0	6.5	<1	<1
				Lime	10.6	6.5	1.5	<1
9/9	Raw Sewage	7.6	35	$FeCl_3$	6.2	11.5	4.0	4.0
				Lime	10.8	14.0	8.0	4.0
	Primary Effluent	6.9	19.0	$FeCl_3$	5.9	5.5	3.0	3.5
				Lime	10.7	7.5	1.8	2.5
	Secondary Effluent	6.8	12.5	$FeCl_3$	5.8	4.8	2.5	1.0
				Lime	10.8	7.0	2.5	2.0

[1]Coagulant dosage: $FeCl_3$ 120 mg/l, lime 250 mg/l

[2]Pulverized Activated Carbon @ 700 and 2000 mg/l for 1 hour then filtered

[3]From ELSA Plant

TABLE 10

Evaluation of The Relative Effects of pH and Pre-Coagulation on The Effectiveness of Treatment of Primary Effluent by Activated Carbon

PRIMARY EFFLUENT (TOC 38 mg/l, 1000 ml samples)

Jar Test No.	1	2	3	4	5	6
Reagent Added	NaOH	NaOH	None	$FeCl_3$	$Ca(OH)_2$	$Ca(OH)_2$
Amount mg/l	-	-		140	420	390
pH Obtained	11.5	11.5	7.9	6.7	11.5	11.5
Appearance after 1 hr settling	Cloudy	Cloudy	Cloudy	Clear	Clear	Clear
Decanted After 1:45 hrs						
pH for Adsorption	7.0*	11.5	7.0*	6.7	7.0*	11.5
TOC of Supernatant mg/l	37	35	33	16	18	15
Treated Supernatant with 2000 mg/l Granular Carbon						
TOC After 1/2 hours.	20	22	20	10	10	11
1-1/2 hours	22	18	23	10	10	10
3 hours	21	17	21	8	9	9

*pH adjusted with HCl

No change in pH observed during adsorption

simple method for recovery that also insures destruction of the usual sewage solids. The sludge from lime coagulation of raw sewage will be thickened and incinerated to destroy the raw sewage organic solids and provide regenerated coagulant. Lime is the preferred coagulant for raw sewage.

A recommended flow sheet for the wastewater treatment concept is given in Figure 33 and a possible plant lay-out in Figure 34. In this scheme, coagulant is added to the raw sewage, and flocculation takes place in a chamber which provides moderate agitation for an average detention time of 15 minutes. Clarification takes place in a sedimentation basin with an average detention time of two hours.

The clarified effluent is then passed through activated carbon adsorption units for removal of dissolved organics. The preferred mode of operation is an expanded bed, which permits the use of simple open-top concrete contacting basins and relatively trouble-free operation. The use of open tanks with trough-type overflows at the surface of the contacting basin provides a means of additional aeration of the wastewater during treatment, thus controlling anaerobic conditions such as those observed in the closed systems in the pilot plant. Two-stage contacting of the activated carbon is proposed to provide efficient utilization of adsorptive capacity by countercurrent movement of the activated carbon within the system. The plant lay-out is based on installing five adsorption units of two stages each. When the granular carbon in the first stage of one unit is spent, that unit is to be taken off stream while the spent carbon is removed and regenerated in the multiple-hearth furnace system provided. During the time this unit is off-stream for the carbon regeneration, the other four units will run at 25% higher feed rate each. Upon completion of the carbon regeneration, the regenerated carbon will be returned to the adsorber which will become the second stage of that unit; the former second stage with partially spent carbon becoming the first stage. Feed would then be evenly divided to the five units until another first stage carbon bed is spent.

The water resulting from the clarification and activated carbon treatment will enhance the quality of surface waters and with chlorination would be suitable for many uses. A final filtration treatment may be desirable to insure a crystal clear effluent for some reuse applications. This post-filtration would remove any suspended matter generated in the carbon columns which might otherwise be released into the final treated water.

The sizes of the various processing units included in the overall treatment scheme are based on the results of this work with one sewage source. It is anticipated that results similar to those reported here can be achieved in larger plants operating on sewage with different characteristics. However, there could

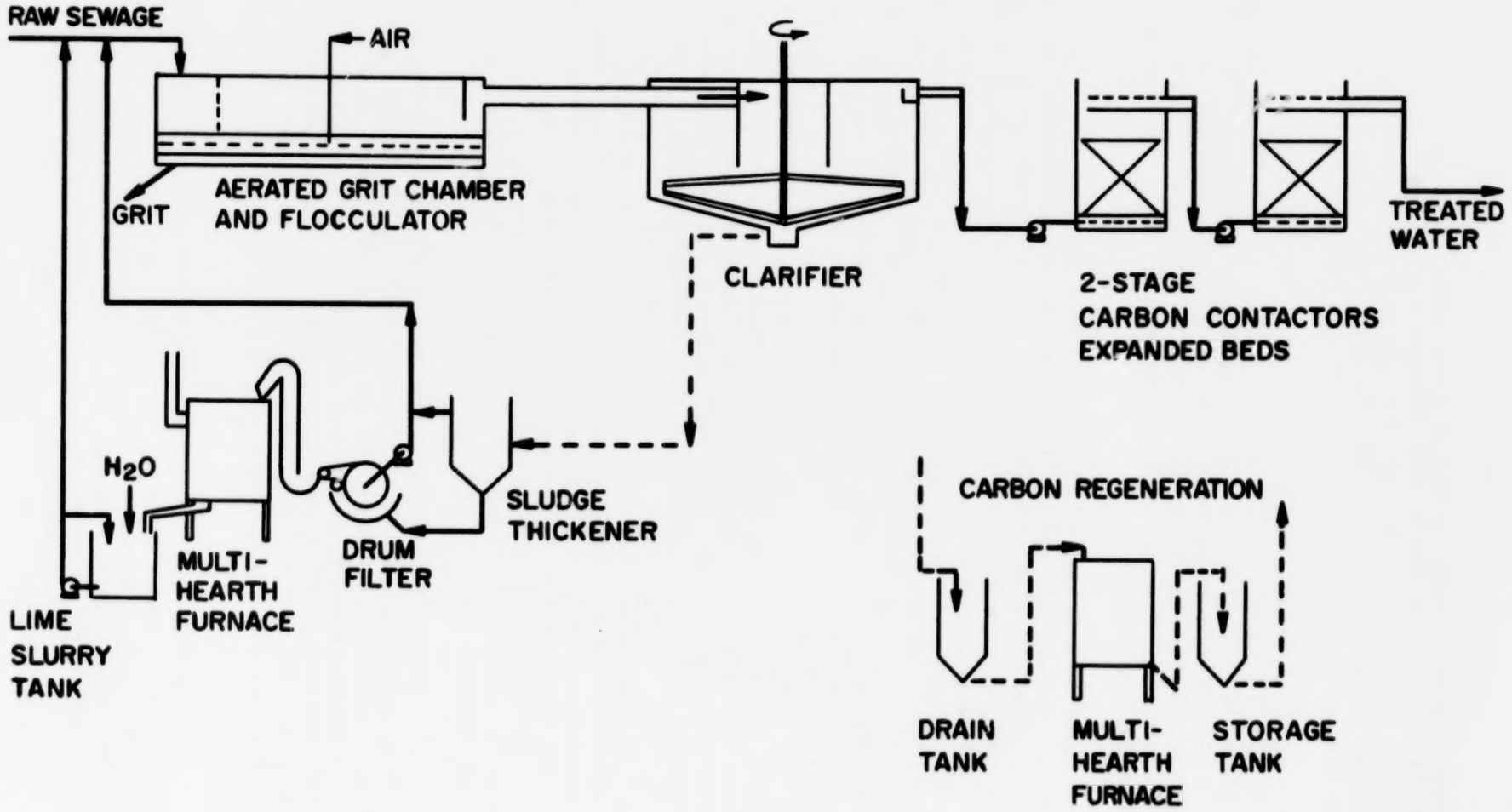

FIGURE 33 PROPOSED SCHEME OF TREATMENT OF RAW SEWAGE BY CHEMICAL CLARIFICATION AND ADSORPTION ON ACTIVATED CARBON

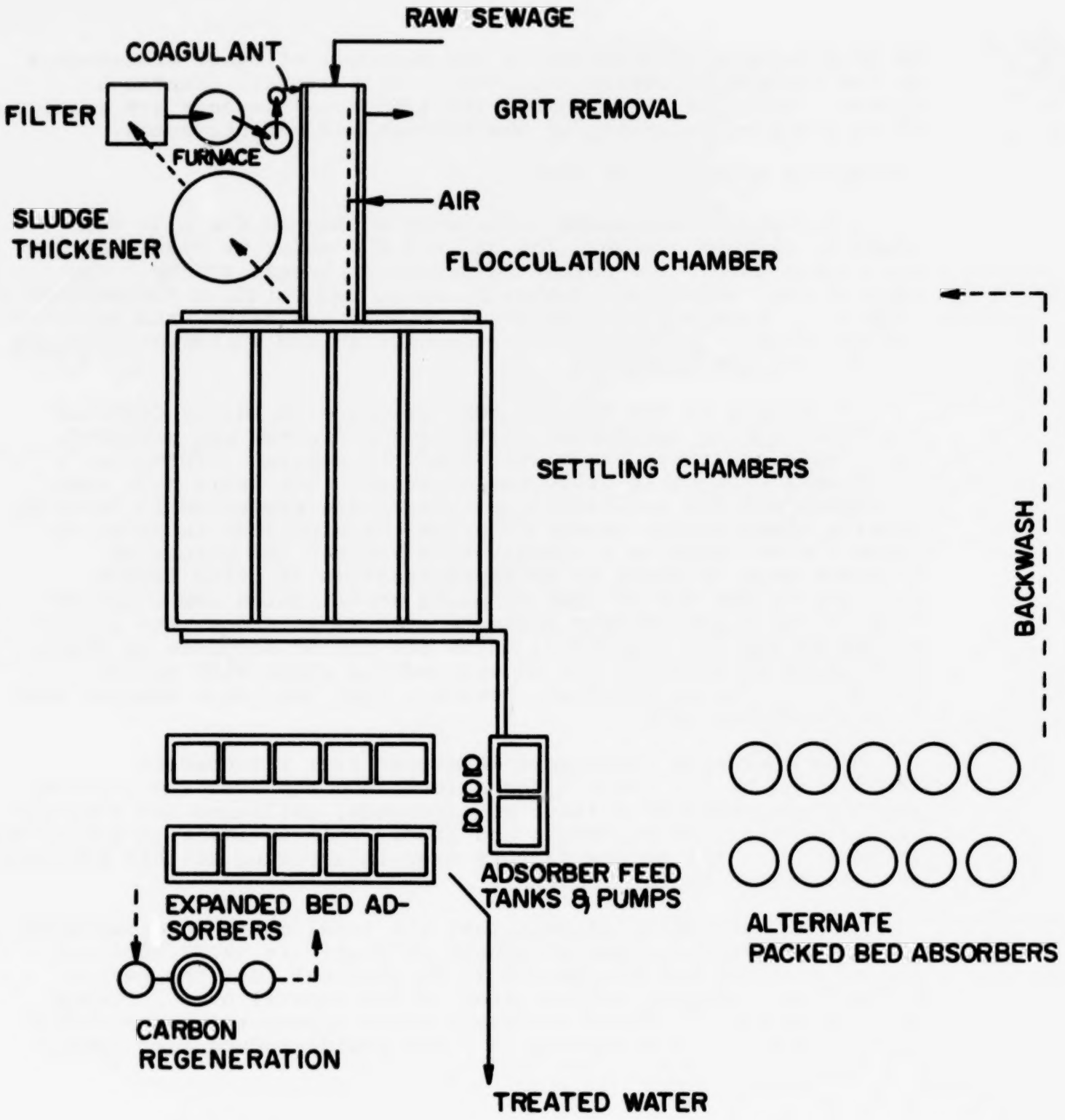

FIGURE 34 PROPOSED ARRANGEMENT OF PROCESSING UNITS

be considerable differences in the response of other wastewaters to the various processes included in this overall treatment scheme. Tests of the process with additional sewages are required to show the universality of the concept and effectiveness.

ESTIMATION OF TREATMENT COST

Capital and operating costs were estimated for a 10 mgd plant to produce a clear, low TOC and BOD water by clarification and carbon adsorption using the proposed process scheme. The capital cost estimates, Tables 11 and 12, included all of the necessary equipment, foundations, buildings, piping and carbon and provisions for utilities. Allowances for engineering and construction costs and profits are included.

To arrive at the capital cost estimate, a fairly detailed breakdown of the individual units in the process was prepared. Then costs for these items were found in several references[14,15,16,17] and a most reasonable price was selected. The individual cost estimates and the individual unit sizes are presented in Table 13. Usually these prices tended to be on the high side in order to place the estimate on a conservative basis. The prices so obtained were adjusted to be representative of price levels expected by the end of 1969 by using an estimated ENR index of 1300.[18] In a preliminary estimate such as this one, the prices estimated for the individual units are not as accurate as those that would be obtained for an engineering study with actual quotations. It is believed, however, that the total capital cost estimate is reliable.

The operating costs were developed from a procedure recommended by the FWPCA[19] for maintenance and overhead charges and include reasonable labor requirements, utilities and supplies including replacement carbon and lime. This estimate is presented in Table 14. All of the factors used in arriving at this estimate are also shown on the table.

These estimates indicate that the total costs for producing a clear, low-carbon, low-phosphate effluent are 19.7¢/1000 gal. for an expanded-bed system and 20.5¢/1000 gal. for the packed-bed system including amortization of the capital over 24 years at 6% interest.[20] These treatment costs appear to be reasonable for the quality of water such a plant would produce from sewage.

TABLE 11

Estimated Capital Costs for Treatment of Raw Sewage by Clarification

Basis: 10 mgd

		Equipment	Piping	Total
Pretreatment and Flocculation		$ 99,800	$ 3,200	$ 103,000
Clarification and Sludge Handling		731,000	13,500	744,500
Plant Cost		830,800	16,700	847,500
Instrumentation	5% equip.	41,500		
Painting and Insulation	2% equip.	16,600		
Buildings and Structures	25% Plant	212,000		270,100
Physical Costs				$1,117,600
Engineering				
Home office	18%	201,000		
Field	17%	190,000		
Contractor	5%	55.000		446,000
Base Costs				$1,563,600
Contingency	15% of Base Costs			235,000
				$1,798,600
Auxiliary Facilities				
Power	@ 100/KW	26,000		
Roads, walks, fence		110,000		136,000
Total Plant Cost				$1,934,600

TABLE 12

Estimated Capital Costs for Treatment of Clarified Raw Sewage by Adsorption in Activated Carbon Beds

Basis: 10 mgd

	Expanded	Packed
Equipment		
Adsorption System	$ 172,900	$ 179,200
Regeneration System	129,900	129,900
	$ 302,800	$ 309,100
Piping		
Adsorption System	$ 195,000	$ 233,000
Regeneration System	13,500	13,500
	$ 208,500	$ 246,500
Total	$ 511,300	$ 555,600
Instrumentation	$ 25,000	$ 28,000
Painting and Insulation	10,000	16,500
Buildings and Structures	127,000	140,000
	$ 162,000	$ 184,500
Physical Costs	$ 673,300	$ 740,100
Engineering		
Home Office	$ 120,000	$ 134,000
Field	115,000	126,000
Contractors	34,000	37,000
	$ 269,000	$ 297,000
Base Cost	$ 942,300	$1,037,100
Contingency 15% of Base Cost	142,000	155,000
	$1,084,300	$1,192,100
Auxiliary Facilities		
Power	$ 25,000	$ 54,000
Fuel Oil	20,000	20,000
Roads, Walks and Fence	60,000	60,000
	$ 105,000	$ 134,000
Total Plant Cost	$1,189,300	$1,326,100
Activated Carbon	288,000	288,000
	$1,477,300	$1,614,100

TABLE 13

Estimated Equipment Costs for Direct Treatment of Raw Sewage by Chemical Clarification and Adsorption

EQUIPMENT COSTS INSTALLED

Pretreatment and Flocculation

NO.		TOTAL COST
1	Bar Screen and Rake	$ 14,000
1	Bypass Gate	5,000
3	Raw Sewage Pumps - 5 mgd each	20,000
1	Grit Removal & Flocculation Chamber 16' x 15' x 60' (15 min.)	28,800
1	Grit Removal Equipment	22,000
2	Aeration Diffusers - 30' long each	3,500
1	Blower - 1,000 cfm 7 psi	6,500
	TOTAL	$ 99,800
	Air Piping	$ 3,200

Clarification and Sludge Handling

1	Clarification Chamber 100' x 100' x 11' deep (2 hrs.)	$ 85,000
4	Tank Equipment - 25' x 100'	155,000
2	Sludge Pumps - 200 gpm each	9,600
1	Sludge Thickener Tank - 25' dia. x 10'	23,000
1	Thickener Mechanism	7,000
1	Sludge Filter - Vacuum Drum 800 ft^2	115,000
1	Sludge Cake Conveyor	2,500
1	Multiple Hearth Furnace - 13' dia. x 8 hearth	300,000
1	Slurry Tank - 16' dia. x 20' deep	4,800
2	Slurry Feed Pump - 100 gpm each	9,600
1	Storage Tank - 2 @ 17' x 17' x 20' deep	19,500
	TOTAL	$731,000
	Piping - Sludge Lines	$ 13,500

TABLE 13 (Cont'd)

Activated Carbon Adsorption Systems

Packed Bed

NO.			TOTAL COST
10	Contactors - 19' dia. x 20' high	$102,000	
	Internal Coating	15,000	
	Underdrain Blocks	14,000	
	Surface Wash System	5,000	
6	Pumps, Main - 5 mgd, 60' head each	36,000	
1	Surface Wash	1,200	
1	Backwash - 4,000 gpm	7,200	
	TOTAL	$179,200	
	Piping Adsorber	128,000	
	Backwash	69,000	
	Transfer Lines	36,000	
		$233,000	
	TOTAL - Packed Bed		$412,200
	Expanded Bed:		
10	Contactors - 17' x 17' x 20' deep	$ 94,400	
	Internal Distributor	36,000	
	Overflow Troughs	10,000	
6	Pumps - 5 mgd, 30' each	32,500	
	TOTAL	$172,900	
	Piping - Adsorber	128,000	
	Backwash	31,000	
	Transfer Lines	36,000	
		$195,000	
	TOTAL - Expanded Bed		$367,900
	CARBON REGENERATION		
1	Transfer Pump - 400 gpm 100 psi	$ 2,200	
1	Transfer Pump - 50 gpm 50 psi	1,200	
1	Drain Bin - 16' dia. x 12'	9,800	
1	Storage Bin - 16' dia. x 12'	9,800	
1	Dewatering Feed Screw	1,900	
1	Multiple Hearth Furnace - 54" 10 x 8 hearth	105,000	
	TOTAL	$129,900	
	Piping	$ 13,500	
	TOTAL - Carbon Regeneration		$143,400

TABLE 14

Estimated Annual Operating Costs for Treatment of Municipal Wastewater by Clarification and Adsorption in Expanded-Bed and Packed-Bed Adsorbers

Basis: 10 mgd

		Annual Cost				
		Pretreat Clarify, etc.	Carbon Treatment Expanded	Carbon Treatment Packed	Combined Expanded	Combined Packed
1.	Operating Labor*	$ 43,300	$ 43,300	$ 43,300	$ 86,600	$ 86,600
2.	Maintenance Labor - 3% Plant Phys. Costs	33,500	20,100	22,100	53,600	55,600
3.	Maintenance Materials - 2% Plant Phys. Costs	22,300	13,500	14,800	35,800	37,100
4.	Maintenance Supplies - 15% of 2 + 3	8,400	5,000	5,500	13,400	13,900
5.	Supervision - 15% of 1	6,500	6,500	6,500	13,000	13,000
6.	Payroll Overhead - 15% of 1 + 2	11,500	9,500	9,800	21,000	21,300
7.	General Overhead - 30% of 1 + 2 + 6	26,500	21,900	22,600	48,400	49,100
8.	Insurance - 1% of Plant Phys. Costs	11,200	6,700	7,400	17,900	18,600
9.	Carbon Makeup - 5% @ $.28/lb	------	27,500	27,500	27,500	27,500
10.	Lime Makeup - 25% @ $20/T	23,000	------	------	23,000	23,000
11.	Fuel - @ $0.50/MM Btu	62,000	13,000	13,000	75,000	75,000
12.	Power - $0.01/kwh	19,500	13,500	25,500	33,000	45,000
13.	Amortization - 24 years @ 6%	154,100	117,500	127,700	271,600	281,800
	Total Annual Cost	$421,800	$298,000	$325,700	$719,800	$747,500
	Treatment Cost - ¢/1000 gal.	11.56	8.164	8.924	19.72	20.48

* 2 shift men + 2 day men @ $4.00 per hour

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